3 Physical Environment and Habitat

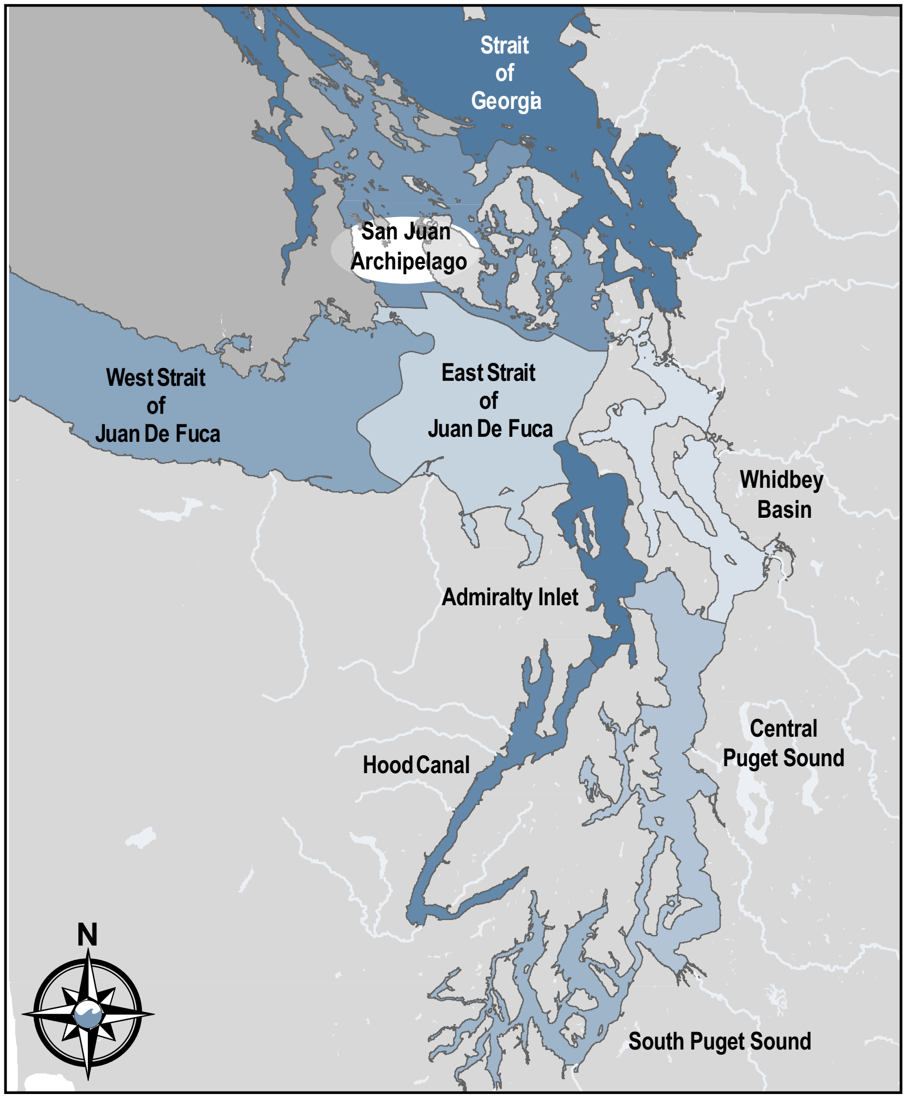
Starfish on rocky intertidal habitat, Oak Bay Park, Jefferson County. | *Toni Weyman Droscher*

1. Overview

Puget Sound is a large inland fjord carved by glaciers, fed by over 10,000 rivers and streams that flow into the Sound from the encircling Cascade and Olympic mountain ranges. The Sound is deep, with average depth of 450 feet (137 meters), and the maximum depth of 930 feet (283 meters) occurring immediately north of Seattle. Ten large rivers—the Nooksack, Skagit, Snohomish, Stillaguamish, Cedar/Lake Washington Canal, Green/Duwamish, Puyallup, Nisqually, Skokomish, and Elwha—flow into Puget Sound and contribute nearly 85 percent of the fresh water that enters the Sound. The unique geology and large dynamic river systems help shape the shoreline, which consists of 2,500 miles (4,023 km) of beaches, bluffs, bays, estuaries, mudflats, salt marshes, and wetlands.

The Strait of Juan de Fuca connects Puget Sound with the Strait of Georgia to the north and Pacific Ocean to the west. Within this region are numerous basins, sub-basins, passages, and bays. To develop a common basis for monitoring and reporting, PSAMP has delineated six main basins in Puget Sound. From the north, the basins are: San Juan Archipelago, the Strait of Juan de Fuca, North Puget Sound (Whidbey Basin and Admiralty Inlet), Central Puget Sound, Hood Canal, and South Puget Sound (Figure 3-1). The boundaries of many basins coincide with sills; for others the demarcation is arbitrary.

Figure 3-1. Puget Sound and the six PSAMP basins referred to throughout this report.



This chapter summarizes climate patterns, stream flows, fresh and marine water quality, modeling efforts and selected restoration activities. It also summarizes several newly established monitoring activities.

Key findings in this chapter include:

- The Pacific Ocean off the west coast of the U.S. experienced two unusual conditions in 2005—a winter-like colder state that persisted through mid-July, followed by ocean warming that resembled a large **El Niño** event. The biological impacts of these alternating atypical ocean conditions in 2005 were significant. Zooplankton stocks were reduced by one half, salmon returns weakened, and sea bird deaths were extraordinarily high among common murre, cormorant, and Cassins' auklet populations. Several subtropical species, such as albacore tuna and Humboldt squid, became common in the offshore shelf waters.
- During the 20th century, the global average **air temperature** rose by approximately 1.1 degrees F (0.6 degrees C). In Puget Sound, the average temperature doubled the global average, increasing by 2.3 degrees F (1.3 degrees C) during the same period.

- Average global **sea surface temperature** has increased by 1.7 degrees F (0.9 degrees C) since 1921.
- Hood Canal, Budd Inlet, Penn Cove, Saratoga Passage, and Possession Sound are locations of highest concern, based on Ecology's **index of water quality** for Puget Sound. Eleven other areas are of high concern.
- Overall **dissolved oxygen** (DO) concentrations in Puget Sound appear to be continuing a downward trend. Very low DO was observed at 14 stations, seven of which had higher DO concentrations in the period from 1998 to 2000. Another seven stations with previously high DO concentrations experienced low DO during 2001-2005.
- **Hood Canal DO** levels measured during 2004 were at the historical low point for any recorded observations. Comparing oxygen data from 1930 through the 1960s with data from 1990 to 2006 shows that in recent years, the area of low dissolved oxygen is getting larger and spreading northwards. Periods of hypoxia are persisting longer through the year.
- **Tidal wetland** losses were documented throughout Puget Sound and at present, approximately 82 percent of the historic extent of tidal wetlands in the region have been lost to development and other land uses.

2. Population Growth and Urban Impacts

One of the major threats to the Puget Sound landscape is the change from native forest cover to urban development, mostly driven by population growth. It is estimated that, in the next 20 years, the population in the Puget Sound Basin will reach over 5 million people (Figure 3-2), which will likely result in significant land conversion and development, increasing the amount of nonporous surfaces in the region. Stormwater runoff from urban development is on of the major nonpoint pollution sources in Puget Sound. Much of the growth as a result of this population increase is likely to occur in the 12 counties that border Puget Sound (Figure 3-3), following a nationwide trend of disproportionate growth in coastal areas.

3. Puget Sound Climate

Much attention is currently focused on the potential impacts of climate change on the Puget Sound region. The answers are not straightforward as the region is subject to complex meteorological and climate regimes that interact with the Olympic and Cascade mountain ranges in the region. This section briefly summarizes the climate trends in air temperature, precipitation, and sea-level rise as reported.

a. Changes in Temperature and Precipitation

During the 20^{th} century, the global average air temperature rose by approximately 1.1 degrees F (0.6 degrees C). In Puget Sound, the average temperature doubled the global average, increasing by 2.3 degrees F (1.3 degrees C) during the same period (Figure 3-4). Much of this change occurred in the latter half of the 1900s. Minimum (colder) temperatures increased more than maximum (warmer)

Figure 3-2. Projected human population growth in Puget Sound. Population growth in the Puget Sound region is projected to exceed twice the 1970 population size by 2025. Much of this growth is taking place in coastal areas. (Source: Washington State Office of Financial Management)

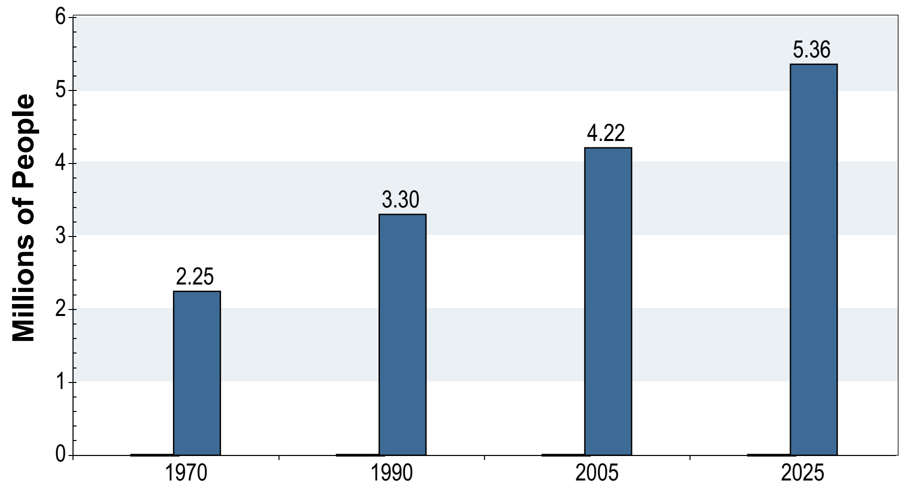
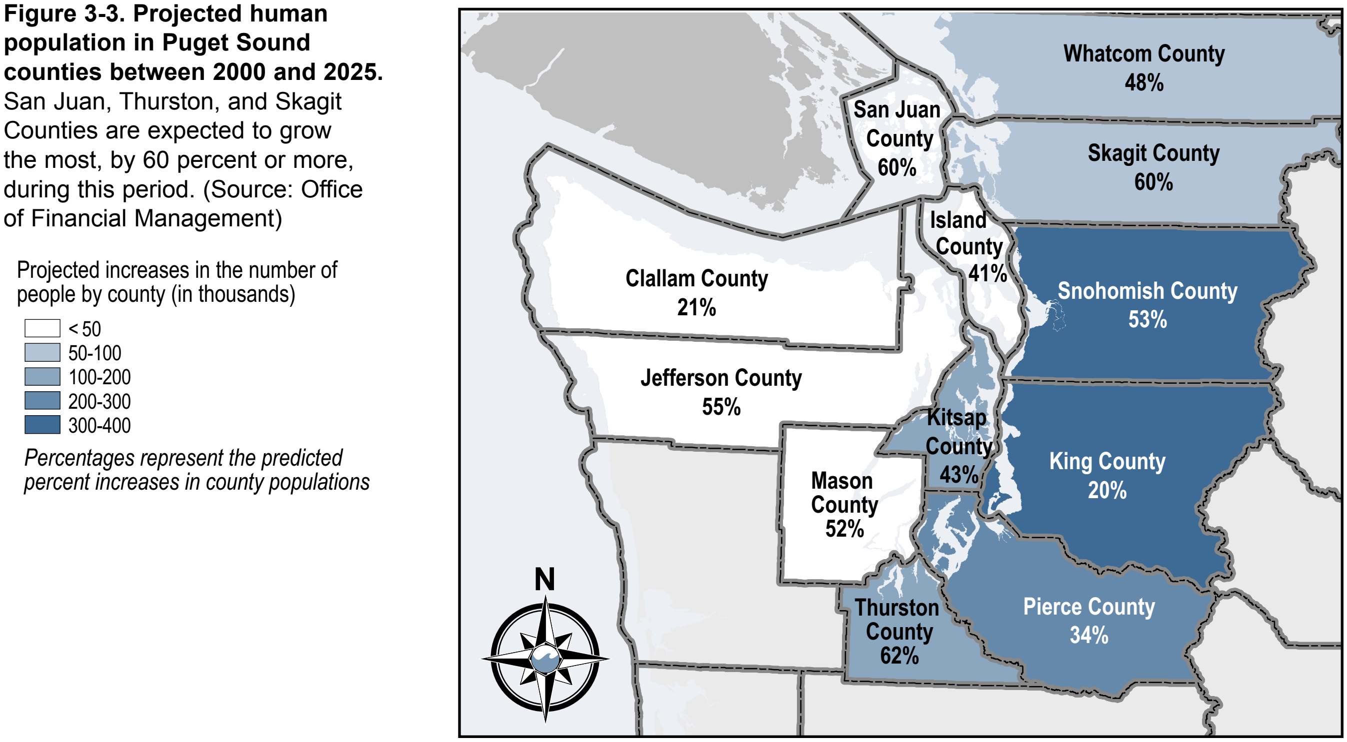


Figure 3-3. Projected human population in Puget Sound counties between 2000 and 2025. San Juan, Thurston, and Skagit Counties are expected to grow the most, by 60 percent or more, during this period. (Source: Office of Financial Management)



temperatures, and, across the Pacific Northwest, winter months incurred the greatest warming. Fall months experienced a smaller temperature increase.

Precipitation patterns do not track temperature changes in the region for the 20th century, and models predict variable increases (between 0 and 10 percent) in precipitation by 2050. Although these projected changes are relatively uncertain, they do fall within the range of variability experienced in the 20th century. However, the timing and possible shift in stream flows that may result from warming temperatures is significant. More precipitation in the Pacific Northwest may fall as rain and any snowpack that does accumulate may thaw earlier in the spring. As river systems and functions alter, the shifted hydrologic pattern may have significant consequences to fish, wildlife, and humans.

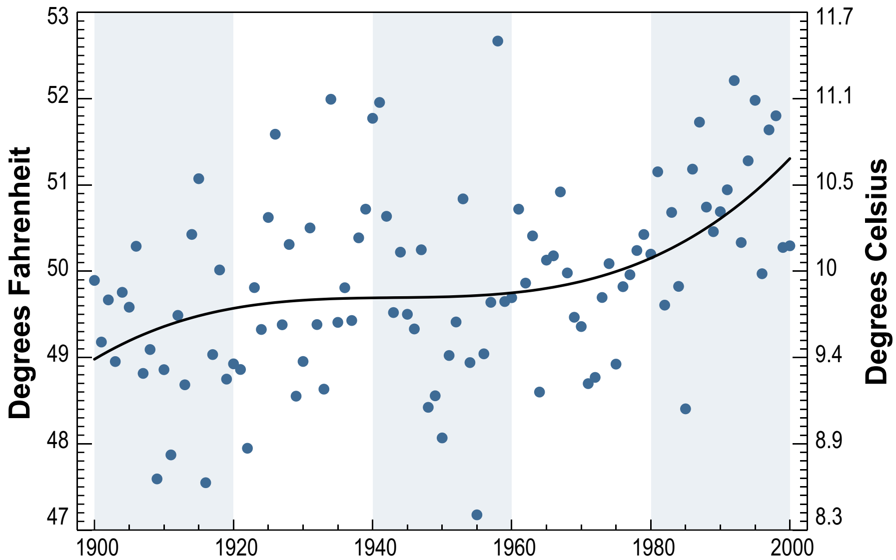


Figure 3-4. Air temperature trends in the Pacific Northwest. Data show an increase of 2.2 degrees F during the 20th century. (Source: PSAT)

b. Potential Sea-level Rise

Sea levels fluctuate over the course of hours, months, and years, with the largest fluctuations occurring during twice-daily tides. Atmospheric pressure and wind patterns, as well as local land movements (caused by subsidence or earthquakes), can drive sea level changes up or down. During the 20th century, the global sea level rose by approximately four to eight inches (10.2 to 20.4 cm) as a result of both the warming of ocean waters (which causes water to expand) and the melting of glaciers, small ice fields, and polar ice sheets (PSAT 2006).

In the Puget Sound region, there are many complex geological factors influencing the rates of sea-level rise. In southern Puget Sound, land is sinking at a rate of more than eight inches (20.3 cm) per century, while in the northern portion of the Olympic Peninsula and Strait of Juan de Fuca, land is uplifting (PSAT 2005). As a result of subsidence and uplift actions, the net local sea-level rise in northern Puget Sound is close to the global average and in southern Puget Sound, it is nearly double the global average.

Models predict that global sea-level rise is likely to accelerate as the planet continues to warm, with changes predicted in the range of four to 35 inches (10.1 to 88.9 cm) during the 21st century (PSAT 2006). Additional sea-level rise in coastal waters, which would affect Puget Sound, associated with changes in winds patterns, may result in an additional eight inches of sea-level rise (Figure 3-5). These coastal changes, coupled with geologically influenced changes in sea level in the south Sound, may mean that portions of Puget Sound may experience sea-level rise as rapidly, if not faster, than the global average rate of sea-level rise.

4. Fresh Water

Freshwater quality characteristics are important controlling factors on the Puget Sound marine environment. Ecology regularly monitors water quality at a number of rivers and streams in the Puget Sound Basin as part of PSAMP. It initiated a freshwater sampling program in 1970 and currently samples 12 water quality parameters on a monthly basis.

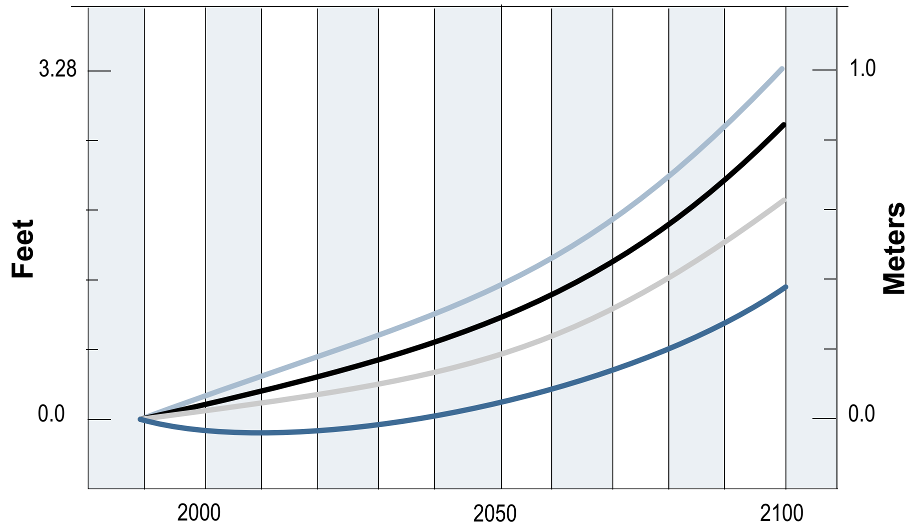


Figure 3-5. Future sea-level rise scenarios for various locations in Puget Sound. The different scenarios reflect the fact that the land masses of southern Puget Sound (including Tacoma) is sinking, while the northern Olympic Peninsula (including Neah Bay) is rising. Depending on the variability in climate factors, sea-level scenarios could be 20 to 200 percent of the mid-range scenario shown here.
(Source: PSAT)

Ecology has been reporting freshwater conditions over the past few years, using a Water Quality Index (WQI) for eight of the 12 regularly monitored parameters (not included are conductivity, nitrate, nitrite, ammonia, and orthophosphorous). In addition, Ecology aggregates results from these individual WQI parameters into a single overall WQI for each sampling station (Hallock 2002). This overall WQI value consists of results from one year of sampling of nutrients (total nitrogen, total phosphorus), pathogens (fecal coliform bacteria), and other physical parameters (water temperature, DO, pH, total suspended solids, turbidity) (Hallock et al. 2004). Information on the physical parameters is presented in this chapter; information on pathogens and nutrients in fresh water is contained in Chapter 5.

a. Freshwater Water Quality Trends

Water quality characteristics of freshwater inputs are important controlling factors on the Puget Sound marine environment. As part of PSAMP, Ecology monitors water quality parameters monthly at 38 river and stream sampling stations in the Puget Sound Basin. Ecology initiated a freshwater sampling program in 1970 and currently samples eight water quality parameters on a monthly basis. These include measures of physical parameters (water temperature, DO, pH, total suspended solids, and turbidity) (Hallock et al. 2004).

Status and Trends

Figure 3-6 displays the overall WQI analysis for the freshwater monitoring stations in the Puget Sound Basin for 2005 (October 2004 through September 2005). The results indicate that fair to good water quality conditions exist in the basin. Fair conditions dominate from the Puyallup River basin northward to the Nooksack Basin. A single station in King County (Fauntleroy Creek, near the mouth) had poor conditions.

The temperature WQI is shown in Figure 3-7. Temperature is an important parameter that influences life-stage development and survival for a number of aquatic organisms. Results show that water temperature conditions were fair in the lower mainstem rivers of King County during 2005. These locations included the Green, Cedar, Snoqualmie, Snohomish, and Stillaguamish rivers.

In general, water temperature has not been a problem in rivers and streams of the Puget Sound Basin. However, this can gradually change with an increasing human

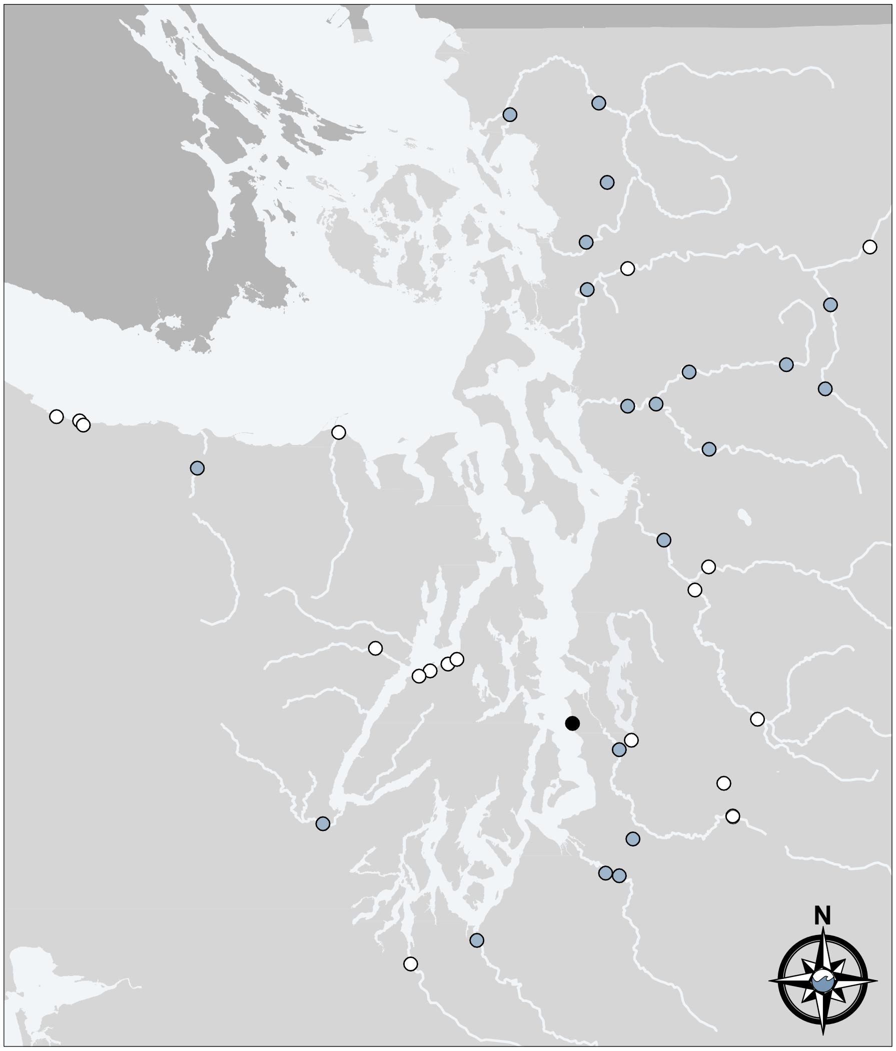


Figure 3-6. Freshwater long-term and rotating monitoring stations and overall Water Quality Index (WQI) scores. Fair to good water quality exists throughout the Sound, with one poor site at Fauntleroy Creek, near Seattle. (Source: Ecology)

● Poor
◉ Fair
○ Good

presence. The ambient air temperature increases in and around cities and will affect streams that run through these areas. Any alterations in seasonal temperature patterns will also affect the smaller streams to an extent that cumulative effects appear in the larger lower mainstems of rivers emptying into Puget Sound or Hood Canal.

Trend analysis based on data collected from 1996 through 2005 showed improvements in overall WQI scores at seven of 24 long-term stations (Figure 3-8). This data do not include Ecology's six rotating stations. There were no significant declining trends in overall water quality for any of the 24 monitoring stations during this 10-year period (Hallock et al. 2006).

5. Stream Flow

a. Historical Changes in Stream Flow

Stream flow is fed by rainfall runoff, stormwater, snowmelt, and groundwater intrusion (where groundwater flows to the surface). Climate patterns in the Pacific Northwest typically result in: higher stream flows from October through January, during peak rainfall; a drop in flows from January through March, as precipitation declines but moisture remains contained in the snowpack; a second peak in early spring, associated with accelerated snowmelt; and low flows through the summer as the snowpack shrinks.

Figure 3-7. Freshwater long-term and rotating ambient monitoring stations and Water Quality Index scores for temperature. Water temperature has not been a problem for Puget Sound rivers and streams in the past decade. (Source: Ecology)

● Poor
● Fair
○ Good

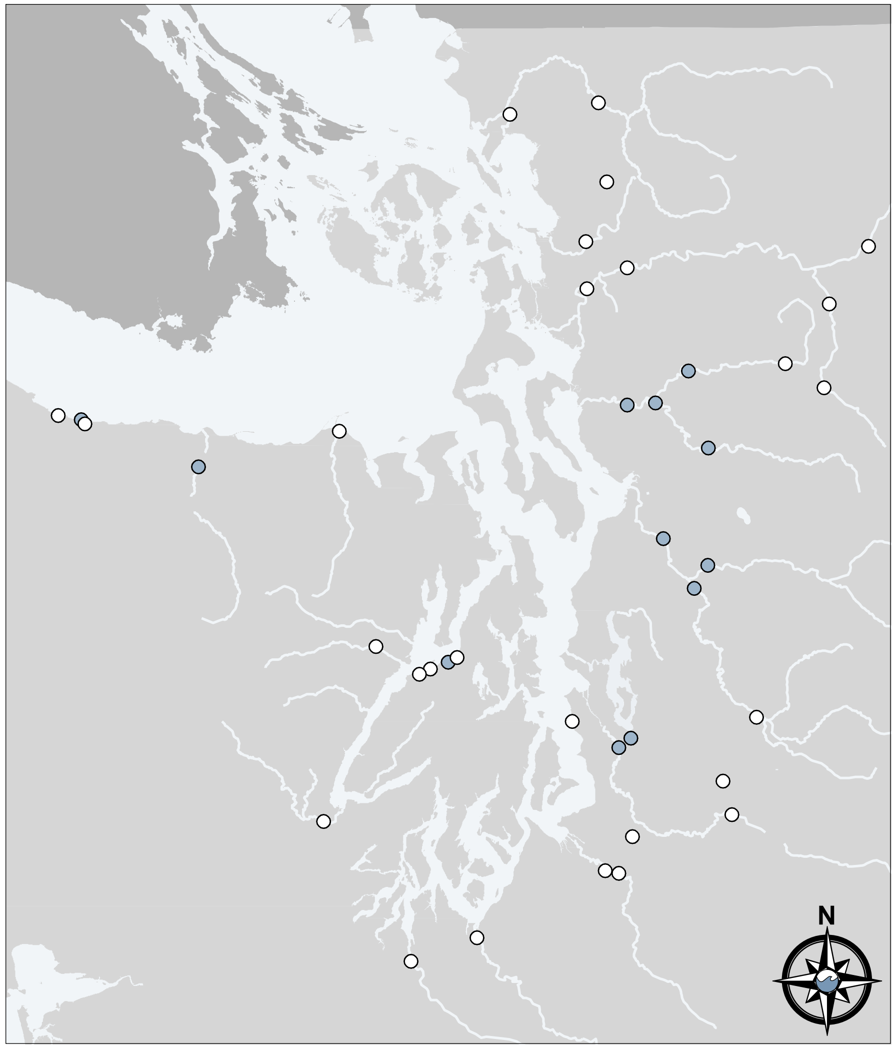
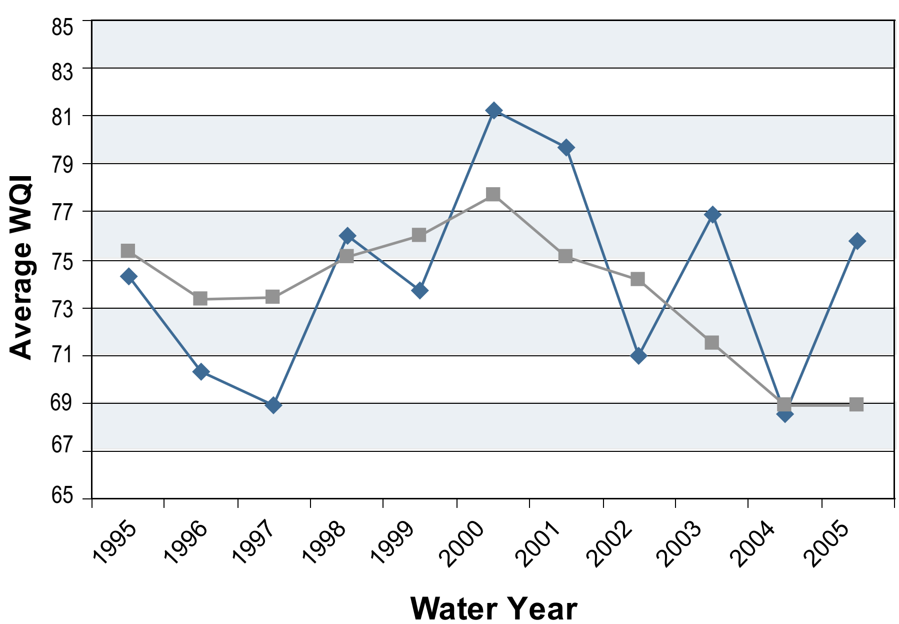


Figure 3-8. Trends in average and flow-adjusted overall WQI scores for 24 long-term stations in Puget Sound. The average WQI adjusted for flow shows an overall improvement (lower WQI score) in the past six years. (Source: Ecology)

Average WQI
Average WQI Adjusted for Flow



Mean annual flow rates for five major rivers in Puget Sound (the Nooksack, Duckabush, Skokomish, Puyallup, and Snohomish) from 1989 through 2005 are presented in Figure 3-9, along with average stream flow for Race Rocks near Victoria, B.C. Stream flow levels vary by river size and extent of watershed, but most track the pattern of precipitation. Additional factors that contribute to stream flow include groundwater discharge, surface water runoff, and hydrologic changes due to land cover conversion.

6. Marine Water

a. Sea-surface Temperature

Water properties in Puget Sound are affected by air temperature, winds, sunlight, river flows, and the properties of oceanic water entering the Sound. Sea-surface (the top layer of marine water) temperature varies seasonally, due to differences in air temperature, cloud cover, wind speed, and solar radiation. Maximum water temperatures are reached during July and August, as air temperatures rise and the amount of solar radiation increases. Conversely, minimum water temperatures typically occur in February. However, in addition to cool weather, water temperatures can be lowered by an influx of deep cold water from upwelling along the outer coast. In the late spring and summer, northerly winds along the Pacific Ocean coast drive upwelling, which brings cold, high-salinity, nutrient-rich water with low DO concentrations closer to the surface. This water enters the Strait of Juan de Fuca and moves through Admiralty Inlet and constitutes the deeper waters in much of Puget Sound.

Since the 1950s, average sea-surface temperature has increased by 1.8 degrees F (1 degree C) at Race Rocks, B.C. (Figure 3-10). If marine water temperatures continue to increase, there may be marked changes in the diversity, distribution, and abundance of plankton that thrive in the upper layers of the marine waters, and this, in turn, may drive other changes in species composition and abundance in the marine food web.

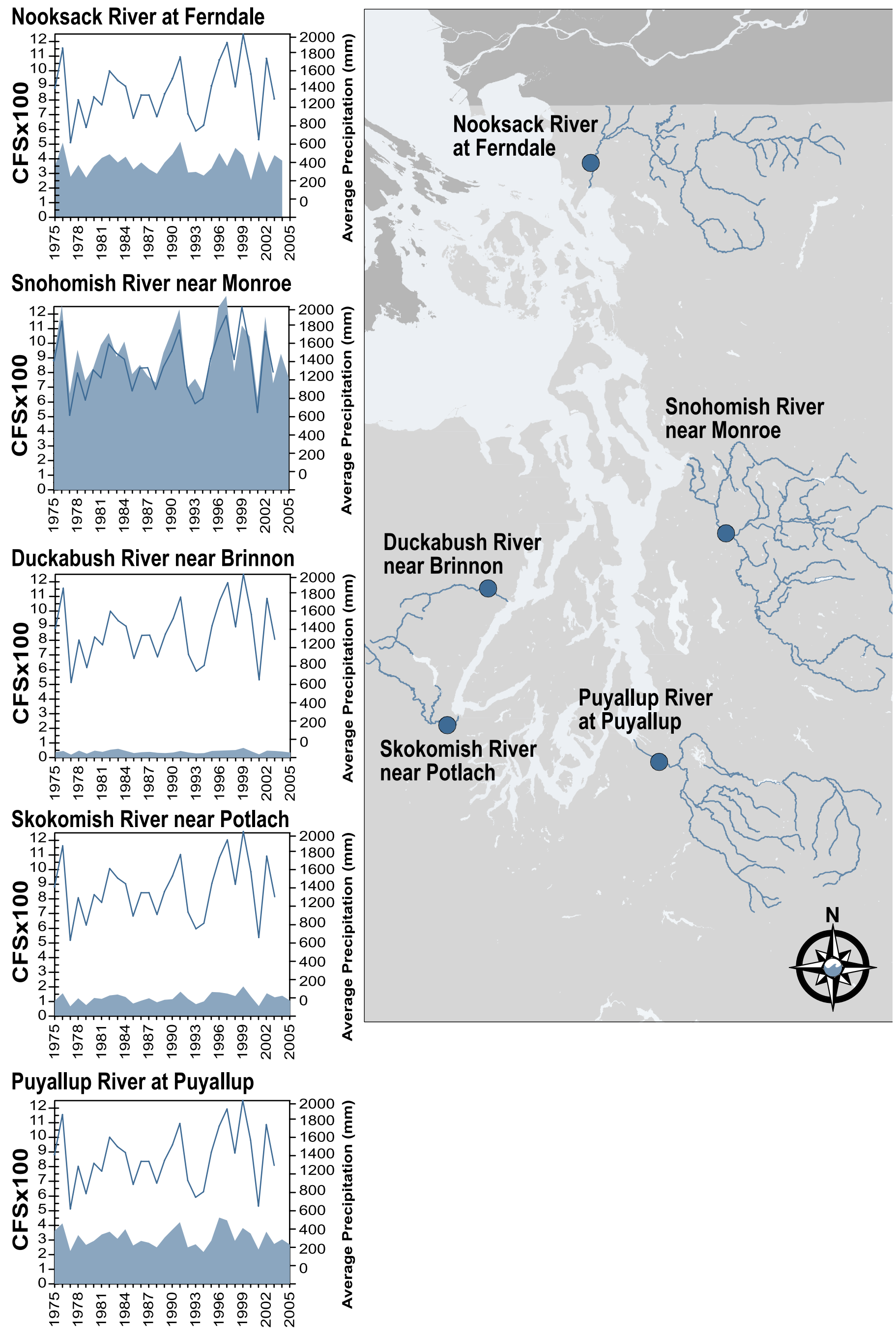
The Pacific Ocean off the west coast of the U.S. experienced two unusual conditions in 2005—a winter-like colder state that persisted through mid-July, followed by ocean temperature warming resembling a large El Niño event. The biological impacts of these alternating atypical ocean conditions in 2005 were significant. Zooplankton stocks were reduced by one-half, salmon returns weakened, and sea bird deaths were extraordinarily high among common murre, cormorant, and Cassins' auklet populations. Several subtropical species, such as albacore tuna and Humboldt squid, became common in shelf waters.

b. Salinity

As with temperature, Puget Sound experiences seasonal variation in salinity. Salinity is usually lowest during the spring and early summer, when the flow of fresh water from snowmelt is at its peak. The highest salinities typically occur in late summer and fall, associated with upwelling (Barnes and Collias 1958) and decreased freshwater flows. From 2002 through 2004, salinities at King County stations ranged from 24.08 to 30.85. As in previous years, the lowest salinity occurred in the surface waters of inner Elliott Bay during the winter and spring, when freshwater inputs from the Duwamish River are at its lowest. The highest salinities occurred from August through December, presumably because of reduced freshwater flows and, possibly, the influx of higher salinity water from upwelling.

Figure 3-9 Stream flow from five major rivers in Puget Sound from 1989 through 2005. Stream flow is shown with average precipitation from Race Rocks, B.C., to illustrate how stream flow generally tracks precipitation. This figure also illustrates the large range of flow in these rivers. There are other contributions to stream flow, such as groundwater discharge, surface water runoff, and alterations in flow associated with changes in landcover.
(Source: PSAT)

Mean Annual Streamflow
Mean Annual Precipitation



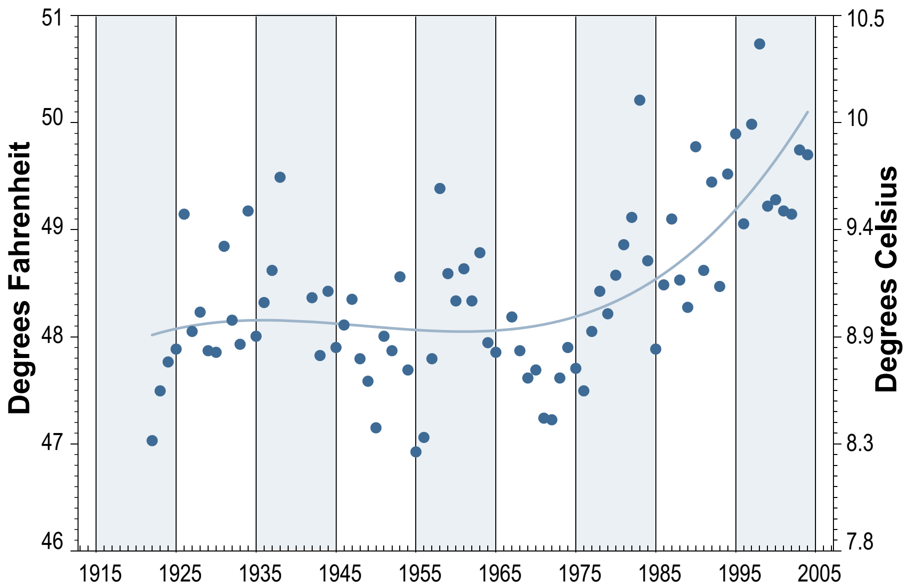


Figure 3-10. Sea-surface temperature measured at Race Rocks, B.C. 1915 to 2005. Average marine water temperature has increased by 1.8 degrees F (1 degree C) since the middle of the previous century, with a steady increasing trend over the last 50 years.
(Source: PSAT)

c. Density

Another important water property, density is affected by both temperature and salinity. Because of the seasonal cycles of temperature and salinity, surface waters have a light density phase during the spring and summer, followed by a dense phase in the fall and winter. Months in which salinities are relatively uniform throughout the water column occur when rainfall is low and input from rivers and runoff is reduced. Changes in density affect the circulation of Puget Sound, including processes such as the flushing of bays and inlets, and have important impacts on a variety of other physical and biological processes, discussed more fully in the next section.

d. Stratification

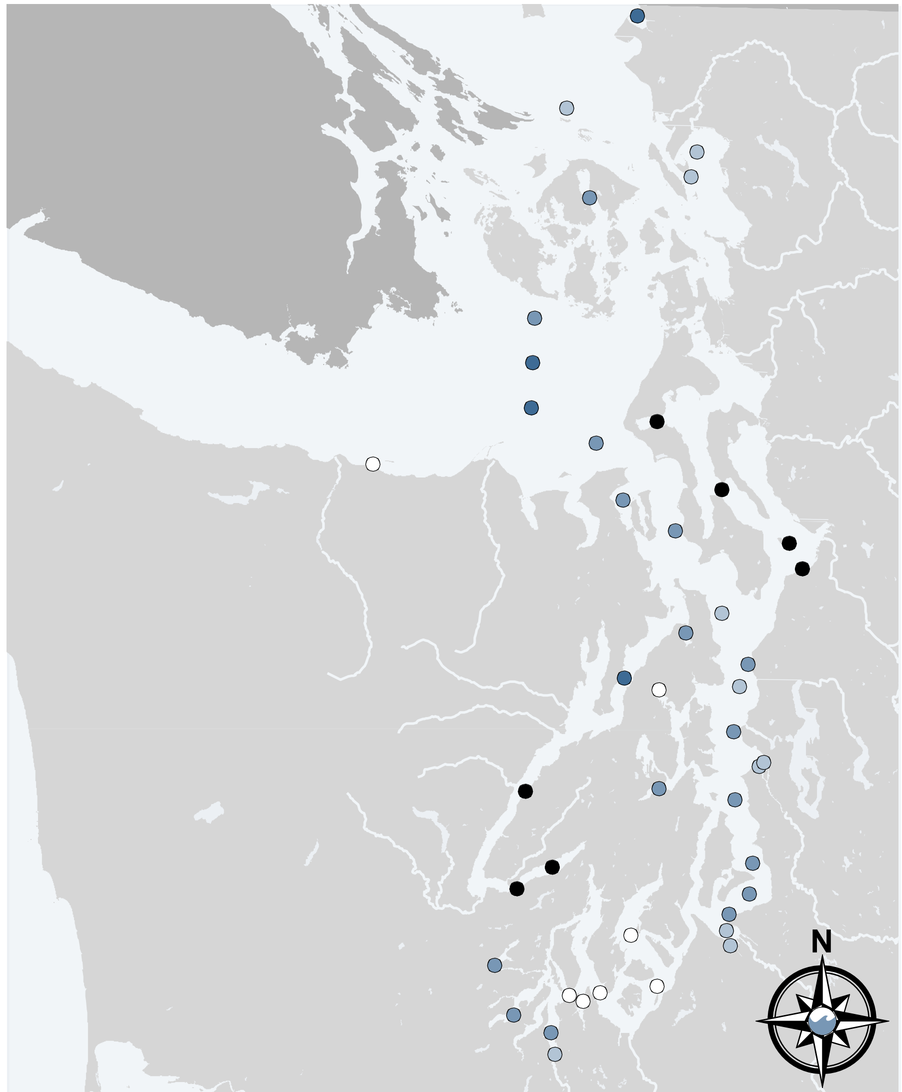
Important properties with widespread effects on water quality are the intensity and persistence of stratification—the layering of waters with different densities (Mann and Lazier 1991). If there are large differences in the density of water from surface to bottom (e.g., when lighter fresh water overlies heavier, cooler, and more saline water), the water column is stratified. In contrast to stratified waters, well-mixed waters show much smaller density differences. The intensity and persistence of stratification is influenced by a variety of factors, some of which include air temperatures, solar radiation, winds, tides, and the amount of fresh water the Sound receives from rain and river flows. In Puget Sound, stratification is most strongly influenced by inputs of fresh riverine water and the amount of solar radiation.

The intensity and persistence of stratification influences physical processes such as mixing and circulation, which, in turn, affect biological and chemical processes that determine water quality. These processes include the development of phytoplankton blooms, the creation and maintenance of oxygen and nutrient gradients, and the prevalence of human-introduced pollutants, including fecal coliform bacteria and ammonium (Newton et al. 2002).

Because stratification is influenced by a variety of atmospheric and oceanographic factors, estimates of its strength and persistence vary from year to year. Nonetheless, overall trends and the relative amounts of stratification at given locations provide important insight into potential changes in Puget Sound.

Figure 3-11. Intensity of water column stratification at marine monitoring stations in Puget Sound, based on 2001-2005 data. Strong and persistent stratification can impact water quality properties, such as dissolved oxygen and nutrient concentrations, by reducing mixing within the water column. More stratified sites are generally located in areas with high freshwater inputs or limited mixing. Sites with moderate or weak stratification occur in areas with high mixing or low inputs of fresh water.
(Source: Ecology and KC DNRP)

Stratification
- Strong and Persistent
- Strong and Intermittent
- Moderate and Infrequent
- Medium and Intermittent
- Weak and Intermittent



Status and Trends

Figure 3-11 shows the intensity and persistence of stratification observed at King County and Ecology marine monitoring stations throughout Puget Sound. Five categories were used to characterize stratification at these stations: strong and persistent, strong and intermittent, moderate and intermittent, moderate and infrequent, and weak and infrequent. These categories reflect the strength of stratification (i.e., the difference in densities between surface and bottom waters) and the amount of time that the water column is stratified at each station. Together, these factors determine the impact that stratification has on physical, chemical, and biological processes at each station.

The stratification properties observed from 2001 through 2005 were very similar to those previously reported for the period from 1998 through 2000. For example, seven of nine stations with strong persistent stratification in 1998 through 2000 retained that classification. The remaining two stations continued to have strong stratification, but the stratification was less persistent than in the previous period. This type of variation is expected because of small year-to-year differences in atmospheric and oceanographic influences on stratification. In general, the most strongly stratified sites were located in areas with high freshwater inputs, and sites with moderate and weak stratification were located in areas with strong mixing or low inputs of fresh water.

A significant drought during 2000 and 2001 resulted in substantially reduced river flows that, in turn, markedly affected water properties. Scientists found a densification (reduction in water density between the surface and bottom of the water column) that appeared throughout the Sound. There were also widespread reductions in stratification, due to higher-salinity surface waters. This observation is notable because stratification regulates numerous biological and physical processes, including the timing of spring phytoplankton blooms, mixing, and flushing. Furthermore, scientists observed that changes in the density gradient in the Strait of Juan de Fuca led to a marked reduction in flushing during the drought year, compared with the higher-flow period of 2001 and 2002. This difference has implications for larval and plankton dispersal and retention, as well as for water quality.

e. Dissolved Oxygen

Oxygen occurs in much lower concentrations in fresh or marine water (in a dissolved state) than in air, and it is just as critical for the survival of marine organisms. In Washington state, the impacts of low DO on marine life in Hood Canal have become the focus of the news media during the past several years, with numerous accounts of fish and invertebrate die-offs associated with episodes of low DO.

Dissolved oxygen concentrations are determined by a series of complex interactions between the biological processes of photosynthesis and respiration and physical factors, such as inputs of fresh and oceanic waters, stratification, circulation, mixing, and the exchange of oxygen across the air/water interface. In the simplest terms, low DO concentrations occur when organic material, primarily dead phytoplankton, sinks and undergoes oxygen-consuming decomposition in waters that are not well-mixed with the atmosphere or more oxygenated waters.

The greatest potential for severe oxygen depletion occurs when high phytoplankton growth rates are fueled by abundant nutrients and strong, persistent water column stratification inhibits mixing. Human contributions of nutrients from excessive fertilizer use, leaking septic tanks, and other sources can dramatically increase phytoplankton growth and subsequent decay, driving dissolved oxygen concentrations at depths low enough to impair or kill marine organisms. Susceptibility to such severe dissolved oxygen depletion varies substantially throughout the Sound. For example, enclosed bays with high nutrient inputs and slow flushing of bottom waters are more susceptible than are open, well-mixed locations.

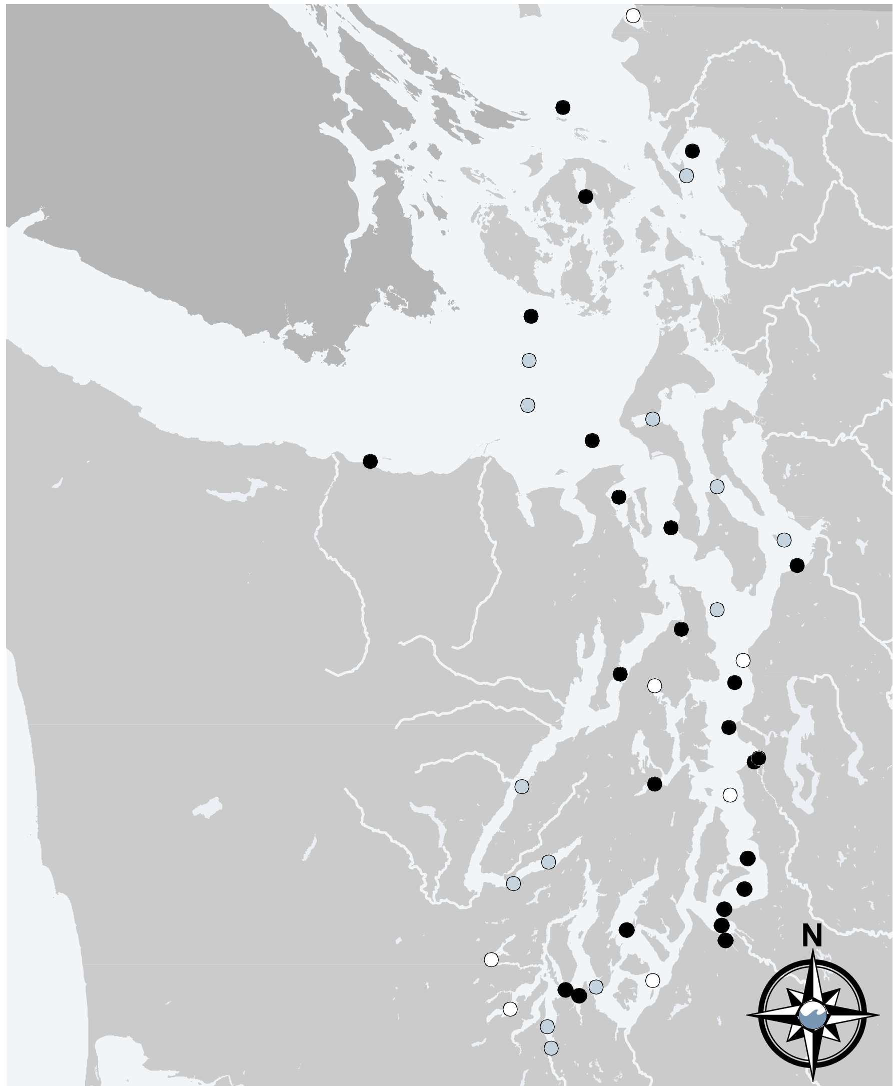
Low dissolved oxygen concentrations can also occur naturally. For example, upwelling along the Pacific Ocean coast during spring and summer typically brings up water with low levels of dissolved oxygen from the depths. When these upwelled waters enter Puget Sound through the Strait of Juan de Fuca and Admiralty Inlet, low bottom water DO concentrations result. However, once in Puget Sound, the levels of DO in these waters may further decline by the human-driven influences described above.

Dissolved oxygen concentrations vary throughout the year, because of seasonal changes in nutrient availability, solar radiation, and water column stratification (layers of water of different density, temperature, and salinity). For example, observations from King County stations in the central Puget Sound Basin have shown maximum near-surface DO concentrations in the upper 35 meters at all stations during the spring and summer. These DO maximums corresponded with

Figure 3-12. Minimum water column DO concentrations at marine monitoring stations in Puget Sound, based on 2001-2005 data. Low DO can potentially cause problems for fish and other marine organisms. Low DO concentrations are affected by strong stratification, slow circulation, increased algal blooms driven by high nutrient inputs, and other location-specific influences, including the influx of Pacific ocean water with naturally low DO. (Source: Ecology)

Dissolved Oxygen

- Very Low
- Low
- Moderate and Infrequent



maximums in chlorophyll-*a* concentration, temporally and spatially, and, therefore, may be attributed to primary productivity. In contrast, minimum dissolved oxygen concentrations were observed below 35 meters in late summer and fall, presumably because of the seasonal influx of dense, low-oxygen Pacific Ocean water and the decay of organic matter from spring, summer, and early fall phytoplankton blooms. Increased water column density stratification in the spring and summer also contributed to low DO levels at depth, by impeding vertical mixing. In fall and winter, as the density gradient breaks down, the water column becomes well mixed, with little variation in DO levels from top to bottom.

Status and Trends

Figure 3-12 shows minimum DO concentrations observed at Puget Sound stations monitored between 2001 and 2005. The data are divided into categories chosen to reflect biologically important concentrations. Five mg/l is often used as the reference concentration at which biological effects can first begin to occur, although effects on growth have been observed at DO concentrations as high as six mg/l in some species. Similarly, a wide range of species experience serious biological effects at DO levels below three mg/l, so this concentration is often used as an indicator of hypoxia. It is important to note that these data represent the single lowest value observed at each station between during 2001 through 2005, so they can inordinately reflect a single good or bad year, rather than showing a continuing upward or downward trend. In addition, most samples were collected monthly during the day, so short-term variability, including nighttime measures, when DO is lowest, is not captured.

Overall DO concentrations in Puget Sound seem to be continuing a downward trend (Figure 3-12), with the proportion of stations experiencing low (> 3 mg/l and <= 5 mg/l) or very low (< 3 mg/l) DO rising from 62 percent between 1998 through 2000 to 84 percent from 2001 through 2005. Very low DO was observed at 14 stations, seven of which had higher DO between 1998 through 2000. Another seven stations with previously high DO experienced low DO from 2001 through 2005. DO oxygen increased at only one station, Bangor in Hood Canal, but movement of the sampling location in response to U.S. Navy security concerns may be the cause, rather than real improvement. Stations located in southern Hood Canal continue to experience very low dissolved oxygen concentrations. Other places with very low DO include Budd Inlet, Penn Cove, Saratoga Passage, Possession Sound, Bellingham Bay, and Nisqually Reach.

Locations with naturally low DO are found in the Strait of Juan de Fuca, the Strait of Georgia, and Admiralty Inlet. The low DO concentrations in these areas reflect the seasonal influx of coastally upwelled water with low dissolved oxygen concentrations into Puget Sound. Other areas with low DO that may be driven more by human activities are Carr, Case, and Budd inlets in southern Puget Sound.

f. Hypoxia in Hood Canal

Hood Canal is a 60-mile-long (100 km) fjord-like basin. It is 300 to 600 feet (90-180 meters) deep and a little over a mile (1.2 km) wide. The canal is a highly productive estuary with strong seawater density stratification and slow circulation (months to a year), compared to the rest of Puget Sound. These conditions are conducive to seasonally low oxygen concentrations (below 2-3 mg/l), known as hypoxia, which have been observed in records dating back to the 1930s. While this phenomenon, or even anoxia (areas of complete oxygen depletion) is not a new phenomenon in Hood Canal, research suggests that this problem has increased in severity, persistence, and spatial extent (Curl and Paulson 1991; Newton, et al. 1995; 2002).

The most severe low DO conditions occur in the southern end of the canal, at the point furthest from water exchange with the rest of Puget Sound. A comparison of oxygen data from 1930 through the 1960s with data from 1990 through 2000s shows that, in recent years, the area of low DO is growing and spreading northwards. Periods of hypoxia are persisting longer through the year (Collias et al. 1974; Newton et al. 2002). Inventories of deepwater oxygen in the southern main stem of Hood Canal (Dabob Bay to Great Bend) for these time periods show that, while variation is evident, the recent data are generally lower; levels measured during 2004 were at the historical low point for any recorded observations. (See Figure 3-13, Appendix C: Color Figures.)

Although records of fish kills in Hood Canal date as far back as the 1920s, repetitive fish kills during 2002, 2003, and 2004 indicate that the increasing hypoxia may be having biological consequences. Two fish kill events in Hood Canal during 2003 galvanized public awareness of the water quality challenges faced by this system. In addition, DNR found that Hood Canal is the only region in Puget Sound to have consecutive years of eelgrass losses since annual PSAMP monitoring began in 2000. Initial findings from 2005 suggest eelgrass declines are more severe in Hood Canal than previously observed, particularly in the southern end of the canal.

Citizen monitoring in Hood Canal

As part of the Hood Canal Dissolved Oxygen Program (HCDOP), the Hood Canal Salmon Enhancement Group, developed the Citizen's Monitoring Program (CMP), which has captured weekly marine water data at established sampling transects along Hood Canal since August 2003. The resultant trend data obtained from the CMP sampling effort have provided a tremendous increase in the understanding of the marine water dynamics. The weekly transect data obtained through the CMP is being used by the HCDOP study to help verify marine biogeochemical models. The near-sea-bed oxygen data from Lynch Cove show the persistence of the hypoxia for multiple years (Figure 3-14).

g. Water Quality Concern

Marine monitoring data are used to assess current conditions and long-term trends in Puget Sound water quality. The water quality variables measured include temperature, conductivity, salinity, density, pH, nutrients, chlorophyll, and light transmission. Various combinations of these variables can be used to rank locations based on water quality concern factors and assess risk of eutrophication, the influx of sewage waste into marine waters, the amount of food available to other organisms in the food web, and pelagic habitat quality. The variables can also be used to determine compliance with federal and state water quality standards.

Ecology uses five indicators to calculate an index of water quality concern: fecal coliform bacteria levels, concentrations of dissolved inorganic nitrogen (DIN), ammonium, DO, and the strength and persistence of stratification. High fecal coliform bacteria levels indicate the presence of a nearby contaminant source. Low DIN levels indicate that phytoplankton growth may be nutrient-limited and, therefore, the water body may be at risk for eutrophication, due to additions of nutrients from human sources. High ammonium concentrations indicate the presence of a nutrient source, and strong and persistent stratification indicates that mixing of surface and bottom waters is reduced. Low DO is a symptom of a combination of stratification strength and high productivity, driven by high nutrient availability. Detailed information on nutrients and fecal coliform bacteria is presented in Chapter 5 of this update.

Status and Trends

Figure 3-15 shows the distribution of waters of concern throughout Puget Sound, based on Ecology and King County monitoring data from 2001 through 2005. To calculate the index, numerical scores were assigned to two threshold values for each indicator, and the total score for all five indicators was calculated. Categorical values for the five indicators at each station are shown in Table 3-1. As in 1998 - 2000, Hood Canal, Budd Inlet, and Penn Cove continue to be locations of highest concern. Hood Canal—southern Hood Canal in particular—has strong, persistent stratification, very low DO, and low DIN concentrations. These indicate that Hood Canal is highly susceptible to increases in phytoplankton productivity, due to changes in nutrient inputs. The 2002 Puget Sound Update reported that it appeared that Budd Inlet could be improving, but this region continues to be a concern, because of strong stratification, very low dissolved oxygen, high fecal coliform levels, and moderate levels of DIN and ammonium. Penn Cove also has had strong, persistent stratification, low DO, and moderate DIN and ammonium concentrations, placing it high on the index of concern.

Saratoga Passage and Possession Sound were also added to highest concern category for 2001-2005. Both locations have experienced strong persistent stratification and very low DO, but Possession Sound also has high fecal coliform

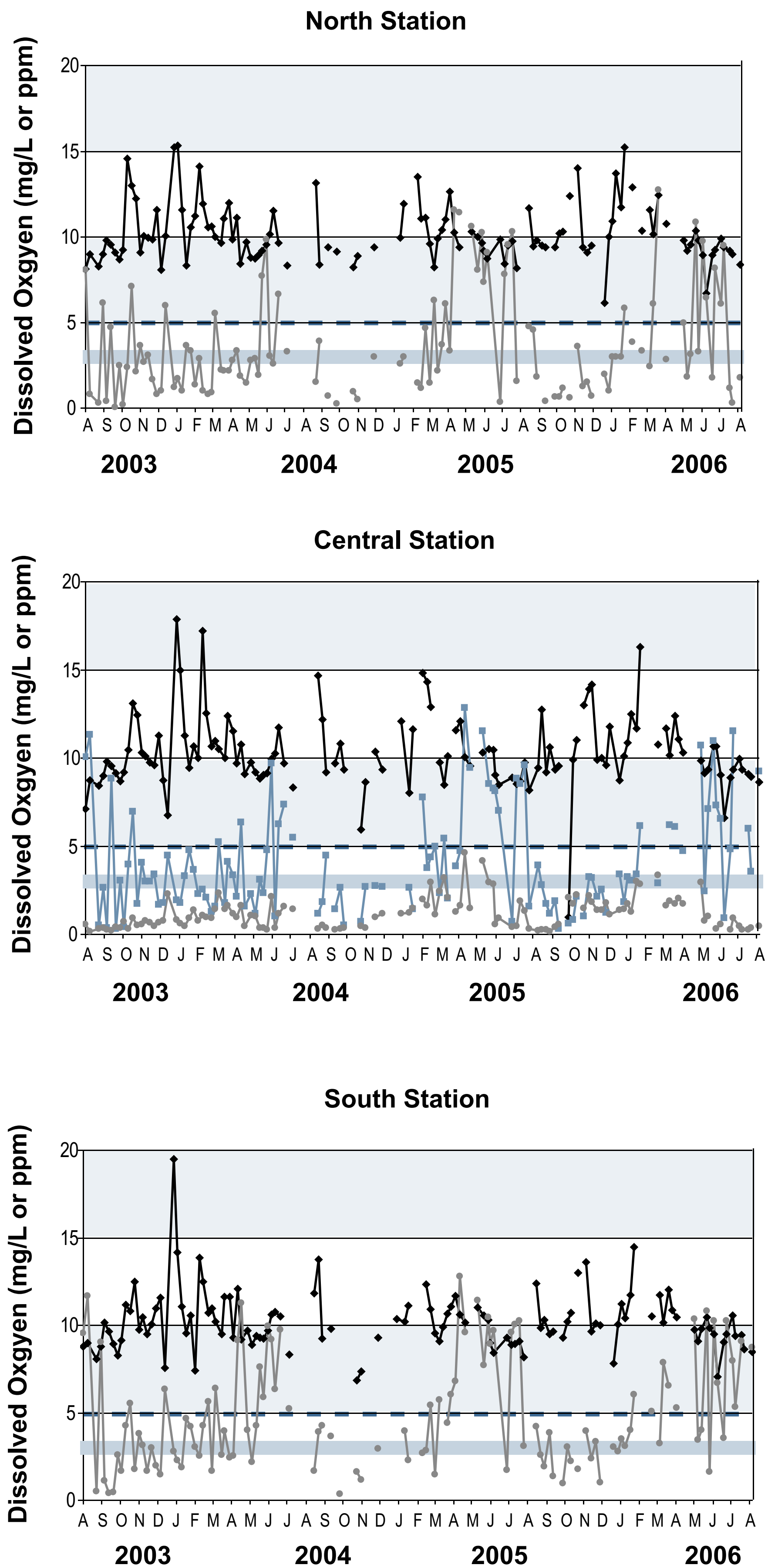
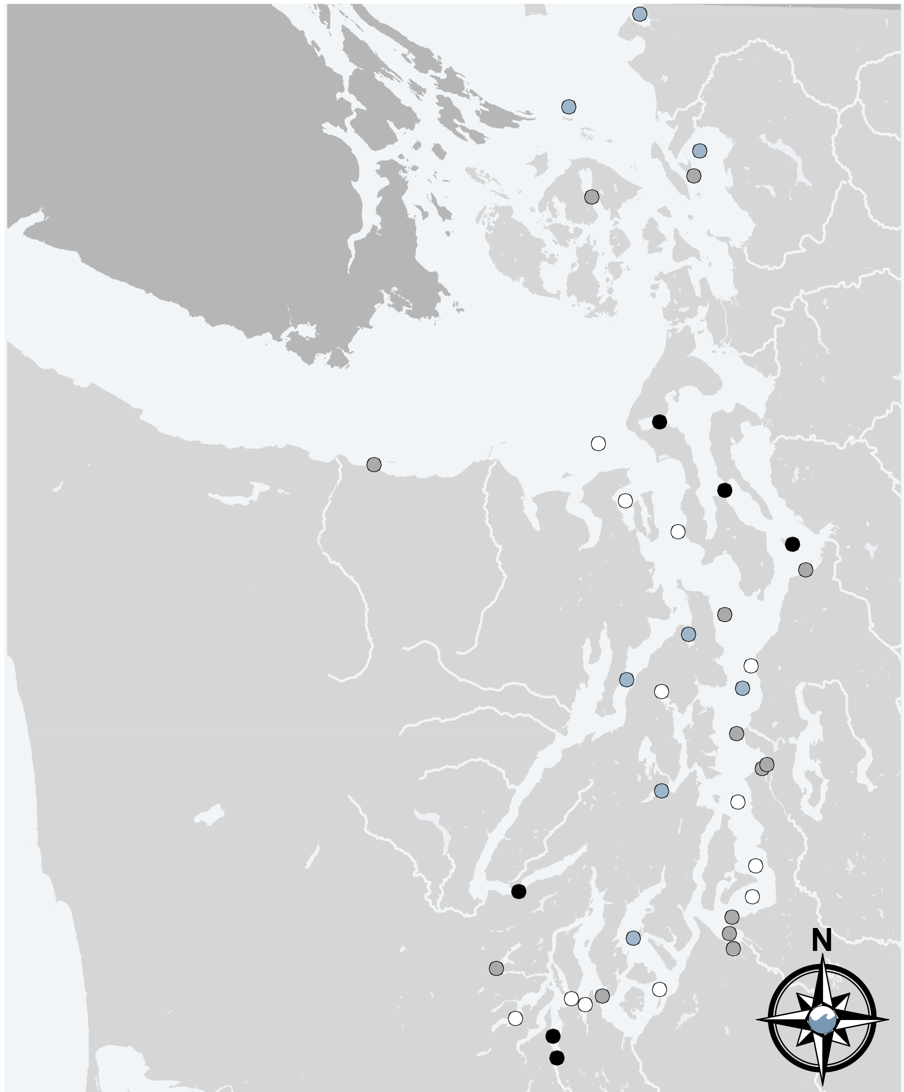


Figure 3-14. Citizen monitoring of dissolved oxygen (DO). Time series of oxygen concentrations at Lynch Cove in Hood Canal, collected weekly by the Citizen's Monitoring Program of the HCDOP-IAM study. While much of the surface water has remained above the stress threshold for biological organisms (5 mg/L, blue dashed line), the mid-column and bottom waters have frequently remained below the threshold for prolonged periods, particularly at the Center station.
(Source: HCDOP)

Figure 3-15. Water quality concern index for marine monitoring stations in Puget Sound, based on 2001-2005 data. Stations are scored by assigning points to each of five indicators. Highest values are given to very low DO, strong stratification, low DIN, high ammonium (NH4), and high fecal coliform levels (FCB). Scores are summed to determine a relative level of diminished water quality, with stations of the highest concern scoring in two or more of these indicators. See Table 3-1 for individual station rankings. (Source: Ecology)



and low levels of DIN. Along with Penn Cove, these stations are located in an area that has strong urban influences and somewhat reduced interchanges of water with the rest of the northern Sound, making them more susceptible to eutrophication and its effects on DO concentrations.

In areas of high concern, which include Commencement, Elliott, and Bellingham bays and other urban locales, as well as less urbanized locations such as Oakland Bay, Nisqually Reach, and East Sound, the causes of concern are more varied, although most of these sites have low DO. However, many of the more urbanized locations have high fecal coliform counts and elevated ammonium levels, feathers typical of waters adjacent to areas with large populations.

Although not located in Puget Sound, Ecology water quality stations in Grays Harbor and Willapa Bay provide an interesting contrast and are included in Table 3-1. These stations vary considerably in their locations within each estuary, ranging from locations near sources of freshwater input to those experiencing relatively direct influences of incoming waters from the outer Pacific Ocean coast. As a result, they also span the range of concerns for marine waters. For example, stations located near the Chehalis River in Grays Harbor and the Willapa River in Willapa Bay are in high or extremely high concern categories because of strong,

Location	DO	FCB	DIN	NH4	Stratification*	WQ Concern
Possession Sound	Very Low	High	Low	Low	SP	Very High
Penn Cove	Very Low	Low	Low	Mod	SP	Very High
Budd Inlet - South Port	Very Low	High	High	High	SI	Very High
Saratoga Passage	Very Low	Low	Low	Low	SP	Very High
Hood Canal - Sisters Pt.	Very Low	Low	Low	Low	SP	Very High
Budd Inlet - Olympia Shoal	Very Low	High	Mod	Mod	MI	Very High
Grays Harbor - Chehalis River	High	High	High	Mod	SP	Very High
Bellingham Bay - Pt. Frances	Very Low	Mod	Mod	Mod	SI	High
Commencement Bay	Low	High	High	Mod	SI	High
Willapa River - Raymond	High	High	High	Mod	SI	High
Willapa River - John. Slough	High	High	High	Mod	SI	High
Quartermaster Harbor	Low	Low	Mod	High	MI	High
Oakland Bay	High	High	Mod	Mod	MI	High
Elliott Bay	Low	High	High	Low	SI	High
Commencement Bay - Browns Pt.	Low	High	High	Low	SI	High
Admiralty Inlet South	Very Low	Mod	High	Low	SI	High
Willapa Bay - S. Jenson Pt.	High	Low	Low	Mod	WI	High
Willapa Bay - Nahcotta Channel	High	Low	Low	Mod	MI	High
West Point	Low	High	High	Low	MI	High
Port Gardner West	Low	Low	High	Low	SP	High
Port Angeles Harbor	Low	High	High	Low	WI	High
Nisqually Reach	Very Low	Low	High	Mod	WI	High
Grays Harbor - South Channel	High	High	High	Mod	MI	High
East Sound	Low	Low	High	High	MI	High
Sinclair Inlet	Low	Mod	Mod	Mod	MI	Moderate
Willapa Bay - Naselle River	High	Mod	Mod	Mod	MI	Moderate
Point Jefferson	Low	Mod	High	Low	SI	Moderate
Carr Inlet	Low	Low	Mod	Mod	WI	Moderate
Bellingham Bay - Nooksack	Low	Low	High	Mod	SI	Moderate
Willapa Bay - Toke Point	High	Mod	Mod	Low	MI	Moderate
Strait of Georgia	Low	Low	High	Low	SI	Moderate
Port Gamble	Low	Low	Mod	Low	MI	Moderate
Hood Canal - Bangor	Low	Low	High	Mod	M Int	Moderate
Drayton Harbor	High	Low	Mod	Mod	M Int	Moderate
Totten Inlet	High	Low	High	Mod	MI	Low
Port Townsend	Low	Low	High	Low	MI	Low
Port Orchard	High	Low	Mod	Low	WI	Low
Point Wells	High	Low	High	Mod	MI	Low
Henderson Inlet	Low	Low	High	Low	WI	Low
Grays Harbor - Damon Pt.	Low	Low	High	Low	MI	Low
East Passage	Low	Low	High	Low	MI	Low
East Passage	Low	Low	High	Low	MI	Low
Dana Passage	Low	Low	High	Low	WI	Low
Admiralty Inlet - Quimper Pn.	Low	Low	High	Low	MI	Low
Admiralty Inlet - Bush Pt.	Low	Low	High	Low	MI	Low
Gordon Point	High	Low	High	Low	WI	Low
Dolphin Point	High	Low	High	Low	MI	Low

Table 3-1. Indicator results and water quality concern index for Puget Sound marine monitoring stations, based on 2001-2005 data. (Index calculations are described in Figure 3-14 and text.) (Source: Ecology)

*Stratification is characterized as:
SP = Strong and persistent
SI = Strong and intermittent
MI = Moderate and infrequent
M Int = Moderate and intermittent
WI = Weak and infrequent

persistent stratification—a result of density differences resulting from incoming fresh water—as well as high fecal coliform concentrations and moderate levels of ammonium. In contrast, the reasons that stations in these estuaries warrant moderate to high concern levels are highly variable. However, the stations share one attribute: none have very low dissolved oxygen concentrations. This variability in the factors most affecting water quality reflects the fundamental differences between Puget Sound and these coastal estuaries, which are shallow, generally well mixed, and have strong tidal exchange with oceanic waters.

7. Circulation

a. General circulation patterns

Central Puget Sound has shallow sills at its northern and southern ends. Sills are shallow submerged piles of debris or rocky ridges formed by retreating glaciers. Major sills beneath northern and central Puget Sound (Admiralty Inlet and the Tacoma Narrows, respectively), and at the mouth of Hood Canal separate Puget Sound from the Strait of Juan de Fuca. Sills are locations where strong mixing and short residence times occur and where water is rapidly transported by tidal currents. The sills alter the normal pattern of estuarine circulation by causing mixing and by restricting the exchange of water with adjacent basins. These alterations contribute to the singular patchiness and productivity of the main basin.

A conceptual flow model of Puget Sound suggests that considerable seaward-flowing surface water from the main basin is mixed downward into the bottom water entering at the southern end of the Admiralty Inlet sill. This process returns the downward mixing surface water to Puget Sound, but as part of the deep water below the sill. This process, known as refluxing, means that some fraction of the water, along with any dissolved and suspended constituents it contains, will not leave the basin immediately, but will make additional trips through Puget Sound. In fact, about two-thirds of the deep water entering the main basin is thought to be main basin surface water caught in the deep inflow during mixing at Admiralty Inlet, rather than water from the Strait.

b. Upwelling

The climate of the northeast Pacific Ocean oscillates between warm and cold states every 20 to 30 years. These changes in state have come to be known as climate regimes. A warm phase dominated most years between 1927 and 1946, with a cool phase dominating from 1947 to 1976 and a warm phase, again, from 1977 to 1998. In the northern California current off Oregon and Washington, these regimes appear to be characterized by low productivity during warm phases (where there is weaker upwelling) and high productivity during cool phases (associated with strong upwelling). The impact of these alternating regimes on salmon, for example, is that both coho and chinook salmon do well under cool regimes and poorly during warm regimes.

Recently, a dramatic reversal of regimes was observed in September 1998, when large-scale cooling was initiated in the North Pacific (Peterson and Schwing 2003). This climate shift led to increased biomass of zooplankton and baitfish, significant increases in survival and return rates of both coho and chinook salmon, changes in recruitment rates of other fishes and increased reproductive success of marine birds. Returns of chinook from 2000 to 2002 were among the highest in recent history. Many scientists postulated that the shift, initiated in late 1998, represented the start of a new cold, productive climate regime. They hoped this event signaled a new 20-year-long cycle of productive ocean conditions, resulting in improved salmon returns. However, this productive regime proved to be short-lived, lasting only four years. Beginning in late 2002, the ocean began to warm and continued to do so through 2005, such that during spring and early summer of 2005, ocean conditions closely resembled conditions observed during the large El Niño event of 1997 and 1998. Warm ocean conditions observed during the summer of 2005 were the result of a lack of significant upwelling until late-July—about two to three months later than average.

8. Current Modeling Efforts in Puget Sound

Models that emulate the circulation, water quality, and other parameters of waters in Puget Sound are important scientific tools for understanding how the Puget Sound ecosystem functions and for predicting future scenarios. A wide variety of local, state, and federal agencies, as well as educational institutions and private entities are involved in the development of circulation models that are used to help us understand basic physical, chemical, biological, and ecological processes, or to guide managers by providing the means for evaluating the effects of different management approaches. Figure 3-16 indicates the general vicinity and target component of the major modeling efforts in Puget Sound.

The following sections provide an overview of several of the modeling projects underway in Puget Sound.

a. Puget Sound Marine Environmental Modeling

The Puget Sound Marine Environmental Modeling (PSMEM) is a partnership of Ecology, UW, King County DNR, EPA, USGS, U.S. Navy, Battelle Pacific Northwest National Labs, NOAA, and the private non-profit Ocean Inquiry Project that seeks to develop predictive circulation and ecosystem models for Puget Sound. The goals of PSMEM are to maintain and operate simulation models, develop a system for managing oceanographic data and model results, facilitate the sharing of resources, and conduct research to develop our understanding of the Sound's working and address questions and issues related to management of the Sound. Current modeling activities by PSMEM members include the development and use of circulation models to:

- Support nearshore habitat restoration efforts, improve fish passage and understand effluent fate and transport in the Whidbey basin area. (Battelle PNNL).
- Evaluate the impacts of increased nutrient loading on south Puget Sound. (Ecology)
- Support TMDL activities and pollutant source control for locations such as Budd Inlet/Capitol Lake and Oakland Bay. (Ecology).
- Support wastewater and sewage management planning in Puget Sound and specific locations such as the Duwamish River estuary and Elliott Bay. (KC DNRP)
- Understand the causes of low dissolved oxygen in Hood Canal and inform possible management actions. (HCDOP-UW, USGS)
- Evaluate fecal coliform loading, transport, and fate to support source management and the evaluation of CSOs in Sinclair and Dyes Inlets. (U.S. Navy)

Figure 3-16. Modeling efforts underway in Puget Sound and the Strait of Juan de Fuca. Included are joint and collaborative modeling.

1. **PRISM:** (UW, King County, DNR, Ecology) and **Brightwater** (King County, DNR). Hydrodynamics, temperature, and salinity. Future additions are nutrients, phytoplankton, zooplankton, and DO for POM-ABC model. Brightwater analysis included hydrodynamics, temperature, salinity, and tracer.

2. **Dyes/Sinclair Inlet:** (PSNS, Ecology). Hydrodynamics, temperature, salinity, and fecal coliform.

3. **Hood Canal:** (HCDOP, UW, USGS, Ecology). Hydrodynamics, temperature, salinity, nutrients, phytoplankton, and DO.

4. **Oakland Bay** (Ecology) Hydrodynamics, temperature, salinity, and fecal coliform.

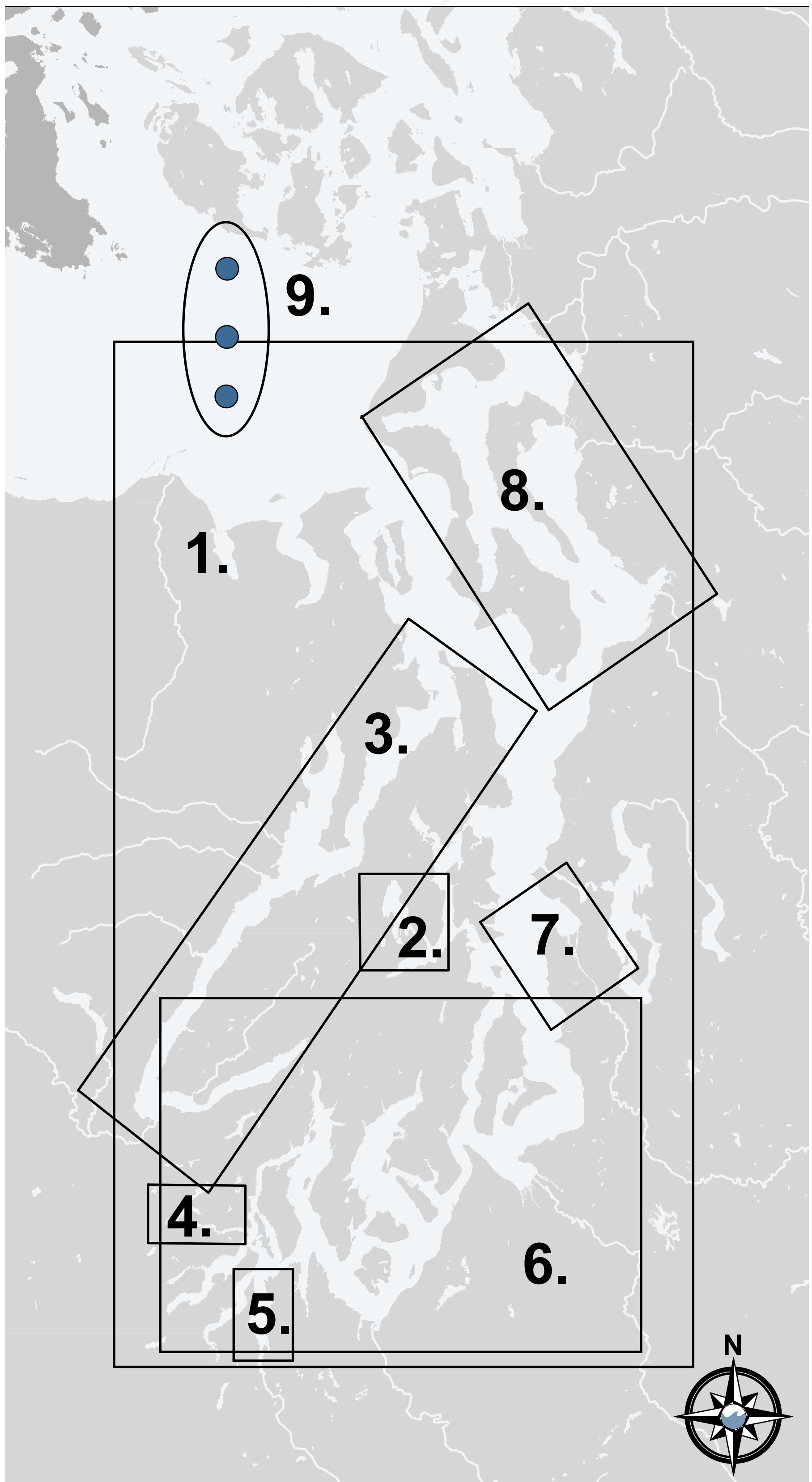
5. **Budd Inlet** (Ecology, LOTT). Hydrodynamics, temperature, salinity, nutrients, phytoplankton, and DO.

6. **South Sound** (Ecology, SPS-MEM). Hydrodynamics, temperature, salinity, nutrients, phytoplankton, and DO.

7. **Duwamish Estuary/ Elliott Bay** (KC, DNR). Hydrodynamics, temperature, salinity, metals, organics, and fecal coliform.

8. **Whidbey Basin** (PNNL). Hydrodynamics, temperature, and salinity.

9. **JEMS** (Ecology, UW-PRISM & UW Friday Harbor). DO, temperature, density and salinity.



- Integrate research and education through the development of a Soundwide Puget Sound Regional Synthesis Model (PRISM). (UW)

b. Modeling Puget Sound Currents

Researchers at the University of Washington are studying Puget Sound currents and developing models to provide a clearer picture of how and where water moves in the Sound. Maps from models can show the movement and spread of water, starting from a given location, as well as preferred paths of movement of water. For example, surface particles released April 1, 2000 in the North Puget Sound and Central Puget Sound basins (Figure 3-17a) and in the Whidbey Basin (Figure 3-17b) are efficiently carried out of the Sound in the outgoing surface layer of the exchange circulation within one to two weeks. The surface waters of the Whidbey Basin are renewed rapidly, because of the large volume of river discharge that this basin receives.

In contrast, particles released in the South Puget Sound Basin (Figure 3-17c) become trapped and are recirculated around Vashon Island and are retained in the region for three weeks or longer, before they head out to Admiralty Inlet or get mixed down to deeper layers by the strong tidal currents in the Tacoma Narrows. There is a distinct front lying between West and Alki Points, which slows recirculation, and only a small portion of the particles cross this barrier after three weeks of drift. (See Figure 3-17, Appendix C: Color Figures.)

Particles can be tracked vertically in the water column, as well as horizontally. Tracking vertical movement of particles reveals regions of large vertical velocities and mixing. Admiralty Inlet is one such region (See Figure 3-18, Appendix C: Color Figures).

Detailed knowledge of patterns of water movement will help in both scientific understanding and practical applications. Flow patterns will control migrations of water-borne organisms, such as plankton, and influence the spread of paralytic shellfish poisoning and certain invasive species. Understanding current patterns and being able to predict them are essential in search-and-rescue operations, oil and contaminant spill response, and other applications.

c. South Puget Sound Water Quality Study

Residential development in south Puget Sound has risen sharply in the past two decades, and the trend is expected to continue. However, there is growing concern that marine water quality in the south Sound may be adversely affected by eutrophication from the increases in nutrient loading that typically accompany urbanization. Hood Canal's chronically low DO concentrations and frequent fish kills have received extensive coverage within the state and throughout the nation. Other areas in the Sound—most notably the South Puget Sound and Whidbey basins—are also at significant risk for similar problems.

The South Puget Sound Basin has numerous blind inlets and is separated from the mouth of Puget Sound by over 60 miles. These factors contribute to long water residence times and slow flushing rates, which limit the dilution and exchange of nutrients and pollutants from the Pacific Ocean. As a result, the South Puget Sound Basin is particularly susceptible to water quality problems, including low DO, reduced water clarity, and algal blooms.

During the first phase of the South Puget Sound Water Quality Study, cruises were conducted in the south Sound to assess the potential for future water quality problems. During the cruises, samples were collected to measure seasonal variability in water quality, analyze point and nonpoint source pollutant loads, and to begin initial development of a hydrodynamic water quality model for the South Puget Sound Basin. Such models allow scientists to track the movement and persistence of pollutants.

Cruise results showed that parts of the South Puget Sound Basin are sensitive to the addition of nutrients and that low DO levels occur in a number of inlets (See Figure 3-19, Appendix C: Color Figures) confirming the potential for serious water quality degradation from increased nutrient loading. Case, Carr, and Budd inlets appear to be most susceptible to eutrophication. Smaller, shallower inlets also showed nutrient sensitivity at times, but strong tidal mixing inhibits the development of low DO. High inputs of other contaminants, such as fecal coliform bacteria, are also a concern in these inlets.

The analysis of pollutant loads found that point sources represented two percent of inflows to South Sound but contributed 30 to 50 percent of the nutrient load. In contrast, only 0.2 percent of the fecal coliform load came from point sources. These results suggest that the combined impact of many small pollutant sources can lead to significant water quality degradation.

For the second phase of the South Sound Study, Ecology proposes to further refine, calibrate, and verify the model for use as an important management tool.

d. Joint Effort to Monitor the Strait of Juan de Fuca

The Strait of Juan de Fuca is where deep in-flowing oceanic waters mix with out-flowing Puget Sound and Georgia Basin surface waters. The Joint Effort to Monitor the Straits (JEMS) is a program that collects water quality data (temperature, salinity, density and DO) from the Strait, enabling valuable comparison of incoming and departing water masses over time.

The incoming ocean water can fluctuate between high-density waters with low oxygen and high nutrient content, versus low-density waters with high oxygen and low nutrient content. These conditions are in response to upwelling and downwelling patterns generated by coastal winds and changes in coastal circulation. High-nutrient/low-oxygen water can mimic conditions that exist during human-caused eutrophication. Therefore, estimates of water quality impairment may be misrepresented if ocean conditions, instead of human-caused nutrient inputs and oxygen drawdown, are responsible.

Moreover, the Strait represents a choke-point on which to monitor in-flowing oceanic waters (deep layer), as well as the integration of out-flowing Puget Sound and Georgia Basin waters (upper layer), enabling valuable comparison of both water masses over time (See Figure 3-20, Appendix C: Color Figures.)

The JEMS oxygen data were recently used by PSAMP scientists to evaluate whether several stations in Puget Sound should be included on the 303(d) list (the State's list of impaired water bodies in Puget Sound). The data are also used to evaluate the extent that ocean-derived oxygen concentration may be influencing hypoxia conditions in Hood Canal.

8. Habitat Modification

Throughout Puget Sound, the threat of habitat loss increases as growth and associated urbanization, agriculture, and resource extraction convert the landscape from native species cover to human-altered landscape. As a result, many land cover types have been dramatically reduced; this may have significant consequences on habitat quality for marine and aquatic species.

a. Changes in Puget Sound Wetlands and Tidal Marshes

Coastal wetland ecosystems are among the most disturbed natural environments. While most coastal wetlands have been lost due to draining and filling, other major impacts include increased nutrient loading (which can lead to eutrophication), changes in hydrology, introductions of toxic materials, and changes in species composition, due to over-harvest and introductions of non-native species (Day et al. 1989; Mitsch and Gosselink 1993; Neumann et al. 2000).

Previous statewide studies suggest than an estimated 69 percent (938,000 acres) of historic wetlands remain in the state (Dahl 2000). However, research focused on estuarine wetlands suggest that a larger proportion of tidal wetlands have been lost (Thom and Hallum 1990). Urban and rural development are the primary causes of estuarine wetland loss, accounting for 43 percent of the losses in Washington (Dahl 2000).

Beginning in 2004, scientists from DNR contracted with University of Washington researchers to characterize the distribution, type, and amount of historic tidal wetlands throughout Puget Sound. The project resulted in spatial GIS maps of wetlands, based on historic and current datasets. Researchers used historic maps to better understand the distribution, character, and amount of tidal wetland habitat loss in Puget Sound. Wetland losses were assessed, both in terms of the loss of wetland area and loss of discrete wetland units (discussed in this document's wetland complexes section).

Status and Trends

Wetlands are found throughout Puget Sound. They are not uniform in their distribution and abundance, with some basins having much higher historical abundances of wetland habitat than others. Some types of wetlands appear to have suffered disproportionately high levels of loss over time. In particular, one type of estuarine wetland (scrub-shrub) and riverine wetlands have declined more than 90 percent from historic levels, and a different type of estuarine wetland (emergent) have declined 67 percent (Table 3-2). Loss of riverine and scrub-shrub wetlands may be attributed to the relative ease (compared to emergent wetlands) with which these wetland types can be converted to developed lands.

From a geographic perspective, all basins have experienced measurable losses of tidal, estuarine, and riverine wetlands. Basins that historically supported the largest amount of tidal wetland habitat include the Whidbey, San Juan Archipelago, Fraser Lowlands, and central Puget Sound (Figure 3-21). The losses of wetland habitat have also been asymmetrical, with the Strait of Juan de Fuca and Hood Canal retaining more than 50 percent of their historical wetland areas, and the San Juan Islands/South Georgia Strait and Central Puget Sound Basins have lost more than 90 percent of their wetland areas (Figure 3-22). One oceanographic basin—the Whidbey Basin—contains more than half of the historic and current wetland areas in Puget Sound, and more than half of the Puget Sound wetland losses have occurred in this basin.

Table 3-2: Amount and type of tidal marsh mapped in Puget Sound for historic and current conditions. Large declines in the total area of tidal wetlands have reduced habitat for many species, including birds and salmon, while changes to the relative abundance of wetland types has increased the importance of remaining scrub-shrub and riverine tidal wetland habitat. (Source: DNR)

Type	Historic Area (acres)	Current Area (acres)	Percent Loss
Estuarine	50,162 (65%)	11,589 (84%)	77
Emergent	34,348 (44%)	11,218 (81%)	67
Scrub-shrub	15,814 (21%)	370 (3%)	98
Riverine-tidal	27,428 (35%)	2,273 (16%)	92
Tidal Wetlands (Total)	**77,590 (100%)**	**13,862 (100%)**	**82**

Note: Percentages in parentheses represent the proportions of total wetlands within each time period.

Figure 3-21. Historic and current wetland area losses. Earliest surveys of wetlands were conducted from the 1850s through the 1890s. The Whidbey Basin includes the Skagit River delta, which underwent significant loss of wetlands through diking, river channel alteration, and land-use conversion, primarily to agriculture. (Source: DNR)

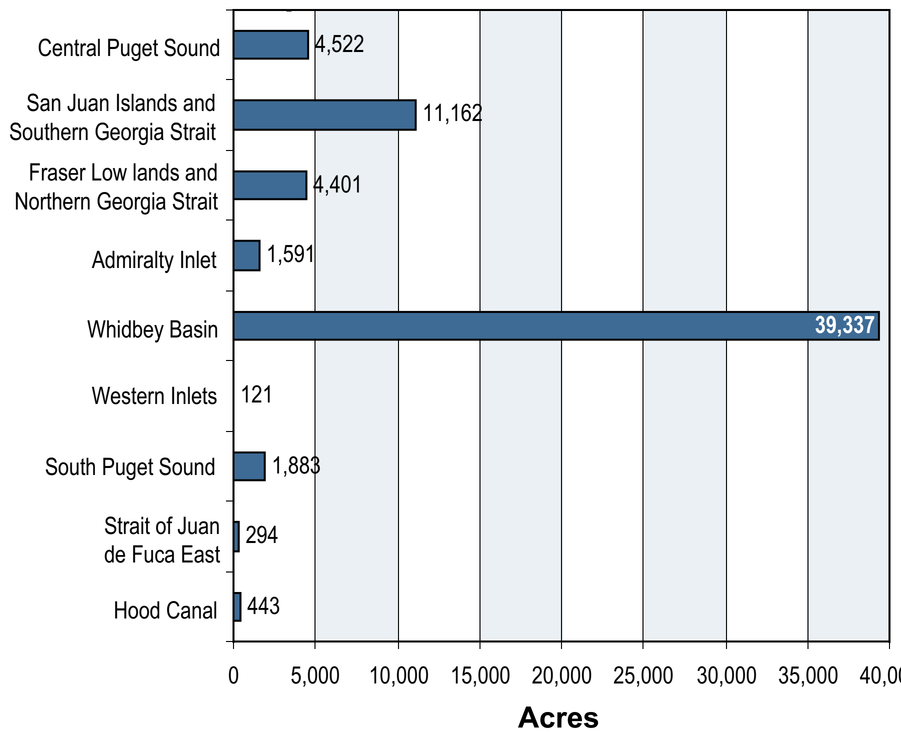
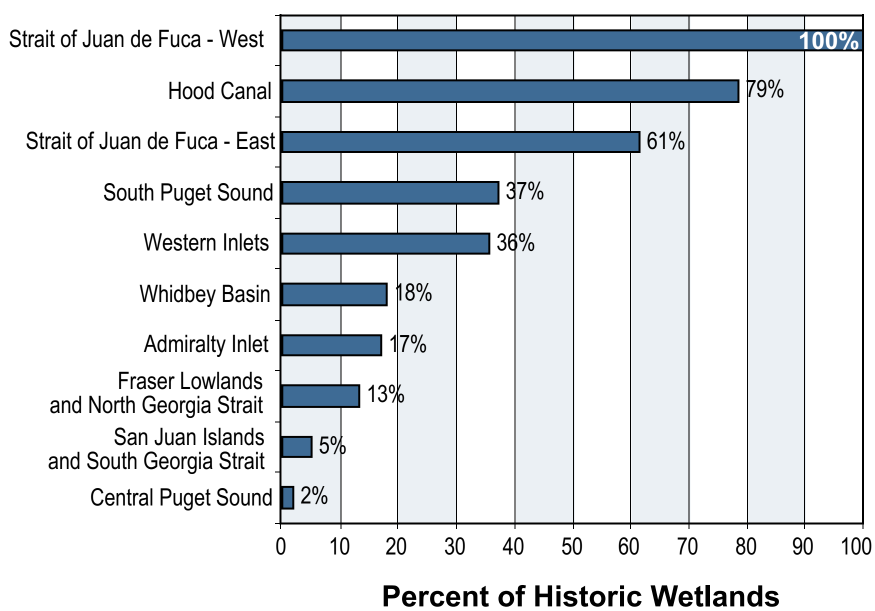


Figure 3-22. Current wetland area as a percentage of historical area. While three basins have more than 50 percent of their historical wetland areas (western and eastern Strait of Juan de Fuca and Hood Canal), wetlands have been nearly eliminated from several basins, with the most impacted basin, Central Puget Sound, retaining only two percent of its historical wetland area.
(Source: DNR)

Note: Due to incomplete historical mapping and/or wetland expansion over the past 150 years, there are more acres of tidal wetlands in the western portion of Strait of Juan de Fuca than mapped historically.



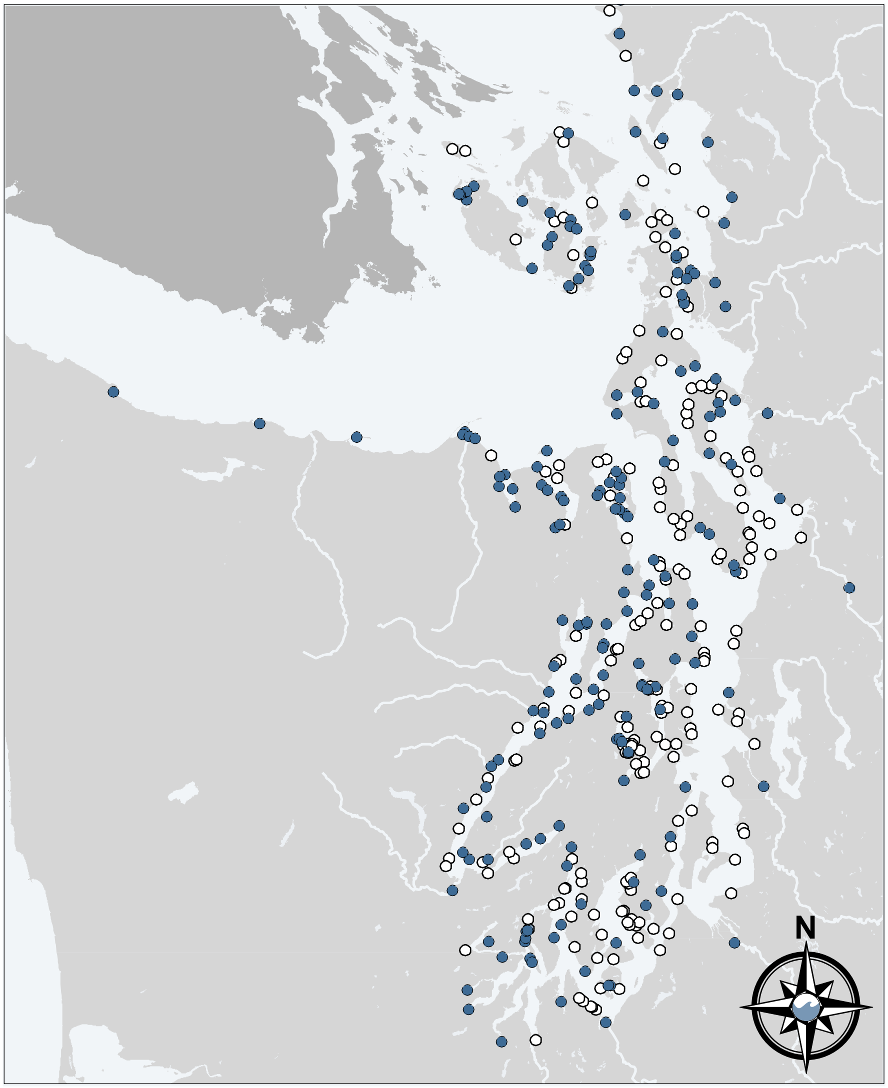


Figure 3-23. Disappearance of wetland complexes in Puget Sound. This includes tidal wetland complexes that have been eliminated since historic maps were created, as indicated by the lighter-colored marks on the map. (Source: DNR)

Tidal Wetland Complexes

- ● Historic wetlands complexes on both historic and current maps
- ○ Wetlands on historical map, not on current map

Losses of wetland complexes appear to be concentrated in areas along the urbanized eastern shores of Puget Sound, between Tacoma and Anacortes. Locales that appear to have experienced the most loss of wetland complexes include central Puget Sound, Whidbey Basin, and the San Juan Archipelago (Figure 3-23).

Calculating the change in wetland area in the western portion of the Strait of Juan de Fuca is not possible, due to challenges comparing current and historic wetland records in this area.

Impacts to the Ecosystem

Tidal marshes are among the most productive ecosystems in the world, providing essential breeding habitat for roughly one-quarter of North American bird species and supporting about 50 percent of the animal species listed as endangered. An estimated 95 percent of commercially important fish and 85 percent of sport fish spend portions of their life cycles in coastal wetland and estuarine habitats (Mitsch and Gosselink 2000).

The loss of tidal wetlands has reduced the productivity of the local ecosystem, thereby restricting the carrying capacity for many species that depend on wetlands for feeding, rearing young, and nesting. Asymmetrical losses in wetland habitats have resulted in a current condition in which scrub-shrub and riverine tidal wetlands have become much less common and remaining fragments are carrying the burden on maintaining populations that rely on these wetland types. Furthermore, species that rely on these wetlands for feeding or refuge now must travel greater distances between wetlands in many areas.

Human Health Consequences

Wetlands offer critical buffers before water reaches, lakes, rivers, and Puget Sound. Pollutants and fertilizers flowing off the landscape are often intercepted and retained by wetland systems. Services provided by wetlands include habitat for species, protection against floods, water purification, and recreational opportunities. Efforts to quantify the economic value of wetlands suggest that bird watching and commercial fish services are the highest-valued wetland services (Woodward and Wui 2001).

b. Fraser River Sediment Plume

The PSAMP long-term monitoring program provides a vital record of sediment conditions in Puget Sound and offers insights into the effects of both natural and human-driven stressors on the Sound. Data from the fixed sentinel stations monitored in this program can raise red flags, highlighting important environmental changes affecting Puget Sound. These results are critical for guiding the policy and regulatory decisions needed to effectively manage and maintain the environmental health of Puget Sound.

Ecology's PSAMP sediment program sampled sediments at 10 fixed stations throughout Puget Sound each spring from 1989 through 2000 (Figure 3-24). Stations were chosen from a variety of habitats and geographic locations in Puget Sound. Sediments from each station were analyzed for particle size, organic carbon content, and the presence of more than 120 chemical contaminants, as well as the types and abundances of sediment-dwelling organisms.

Large-scale changes in grain size and the numbers and types of sediment-dwelling organisms were observed at the Strait of Georgia station and appeared to be linked to natural, rather than human-caused stressors.

Status and Trends

From 1989 through 1995, the amount of fine-grained sediment (percent silt) at the Strait of Georgia station varied between 25 and 50 percent. Between 1995 and 1997, it rose to approximately 90 percent, then declined to about 50 percent between 1998 and 2000. During the study, the community of sediment-dwelling organisms changed from one characterized by the annelid worm species *Prionospio*, *Pholoe*, and *Cossura*, to one consisting primarily of *Cossura*—a mobile, burrowing worm that tolerates living in a wide range of sediment grain sizes. The community finally changed to one dominated by the bivalve mollusks *Macoma* and *Yoldia*, also active burrowers (Figure 3-25).

Examination of the flow and discharge plume of British Columbia's Fraser River, which can carry heavy sediment loads into the Strait of Georgia (See Figure 3-26, Appendix C: Color Figures), suggested a possible cause for the observed changes. Annual rainfall, Fraser River flow volumes, and the percent silt at the Strait of Georgia station all exhibit similar temporal patterns (Figure 3-25).

It is hypothesized that the changes in the sediment community observed in the Strait of Georgia were driven by above-average precipitation in 1996 and

Figure 3-24. Location of 10 long-term sediment monitoring sites in Puget Sound.
(Source: Ecology)

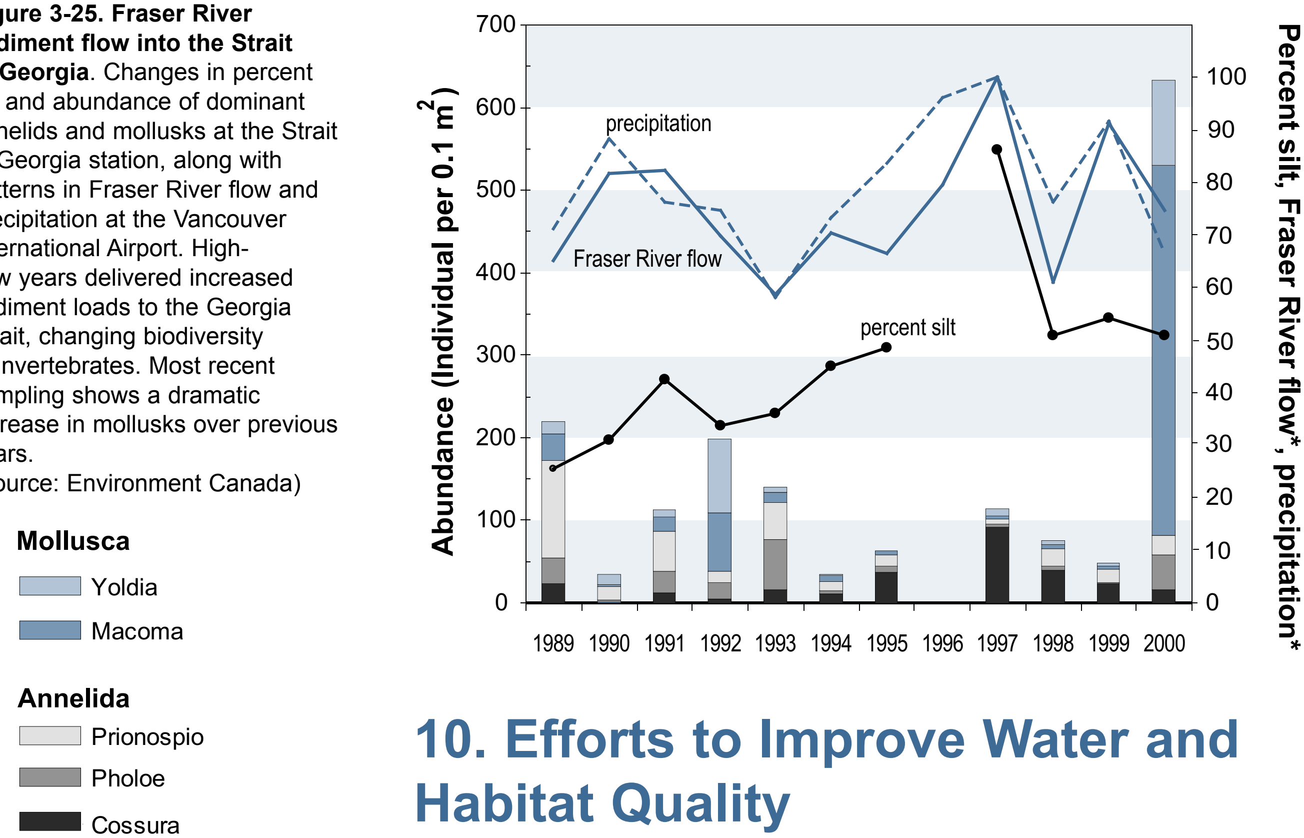
1997, which increased water flows in the Fraser River and resulted in increased deposition of fine sediments in northern Puget Sound. Changes in grain size are known to influence community structure. The increase in fine sediments at this station may be associated with increasing numbers of active burrowing organisms.

Impacts to the Ecosystem

Changes in the sediment community in the Strait of Georgia, in response to naturally occurring variation in rainfall and river flow, clearly show the value of long-term monitoring for furthering our understanding of the effects of stressors on the Puget Sound ecosystem.

Understanding these processes on a local scale can help explain similar changes in other regions. For example, the sediment and community changes observed in the Strait of Georgia may hold the key to understanding recent declines in San Juan Island eelgrass populations. Acting on the results of this study, investigators from the University of Washington and the USGS conducted sediment surveys in June 2006 to determine if the decline in eelgrass abundance can also be linked to the deposition of fine-grained sediments from the Fraser River (S. Wyllie-Echeverria, pers. comm.).

Figure 3-25. Fraser River sediment flow into the Strait of Georgia. Changes in percent silt and abundance of dominant annelids and mollusks at the Strait of Georgia station, along with patterns in Fraser River flow and precipitation at the Vancouver International Airport. High-flow years delivered increased sediment loads to the Georgia Strait, changing biodiversity of invertebrates. Most recent sampling shows a dramatic increase in mollusks over previous years.
(Source: Environment Canada)



* Flow and precipitation values for each year are represented as their percentage of the corresponding 1997 values.

10. Efforts to Improve Water and Habitat Quality

There are many restoration activities underway in Puget Sound, carried out by federal, state and local agencies, and citizen groups. Progress on many of these restoration projects is reported elsewhere. The following descriptions of restoration projects and conservation tools are a small subset of the projects underway in Puget Sound.

a. Elwha Dam Removal

Between 1911 and 1913, two dams were built on the Elwha River, one of 10 major rivers on the Olympic Peninsula. The dams effectively blocked 10 runs of anadromous fish from returning to over 70 miles of spawning habitat in the upper Elwha River. Prior to dam construction, the Elwha was one of the most productive salmon rivers in the Puget Sound region, with runs numbering in the hundreds of thousands (Wunderlich et al. 1994). Without fish passages at either dams, salmon spawning is limited to the lower 4.9 miles of the river. Currently approximately 4,000 wild salmon now spawn in a stretch of river between the lower dam and the Strait of Juan de Fuca.

The dams have also prevented downstream transport of sediments and nutrients, greatly altering structure and composition of the river's riparian areas, delta, and beaches at its mouth. About 13.8 million cubic yards of sediment are trapped in Lake Mills, and up to four million cubic yards are trapped in Lake Aldwell. This sediment will be permitted to naturally move downstream as the dams are deconstructed.

Impacts to the Ecosystem

Dam removal will begin in 2007, and the resulting restoration of the Elwha River will open up over 70 miles of largely pristine salmon habitat. There are estimates that the removal of the two dams would produce approximately 390,000 salmon and steelhead in about 30 years, compared with less than 50,000 fish if the dams were fitted with upstream and downstream fish passage facilities.

b. Derelict Fishing Gear Removal

Derelict fishing gear is lost or abandoned nets, pots, and fishing line that are found in the marine environment. As of March 2006, the Northwest Straits Commission (NWSC) completed 41 days of survey operations, covering 25 square nautical miles of seabed. In this area, which represents less than five percent of Puget Sound fishing grounds, over 3,500 derelict crab pots and 32 nets were encountered. Although it is not known how much derelict gear is in Puget Sound, it is estimated that only three percent has been located and less than one percent removed. NWSC has set goals of 2,500 tons of derelict pilings and 800 tons of beach debris to be removed throughout Puget Sound. Most of the beach projects will continue to be sited in the Northwest Straits, and the piling efforts will be spread out through the Sound.

Status and Trends

In 2002, NWSC initiated a pilot project to develop and test protocols for locating, removing, and disposing of derelict fishing gear. It partnered with the WDFW to set up a reporting system that includes a telephone hotline and Web site. From underwater surveys and public reporting of gear, over 3,400 pieces of derelict have been entered into a database, and 1,041 of these pieces have been removed. Removals include: 361 gillnets, 3 purse seine nets, 1 aquaculture net, and 945 crab pots. By removing derelict nets, over 73 acres (30 hectares) of underwater marine habitat have been cleaned up. The nets contained a total of 1,469 marine invertebrates, 102 marine birds, 372 fish, and eight marine mammals. Crab pots contained over 1,560 live and dead marine invertebrates and other animals. These numbers represent only the marine life that was on the gear at the fixed point in time when removal occurs. There are no data available to identify how many animals are caught, killed, and subsequently, decompose while such gear is in the water.

Impacts to the Ecosystem

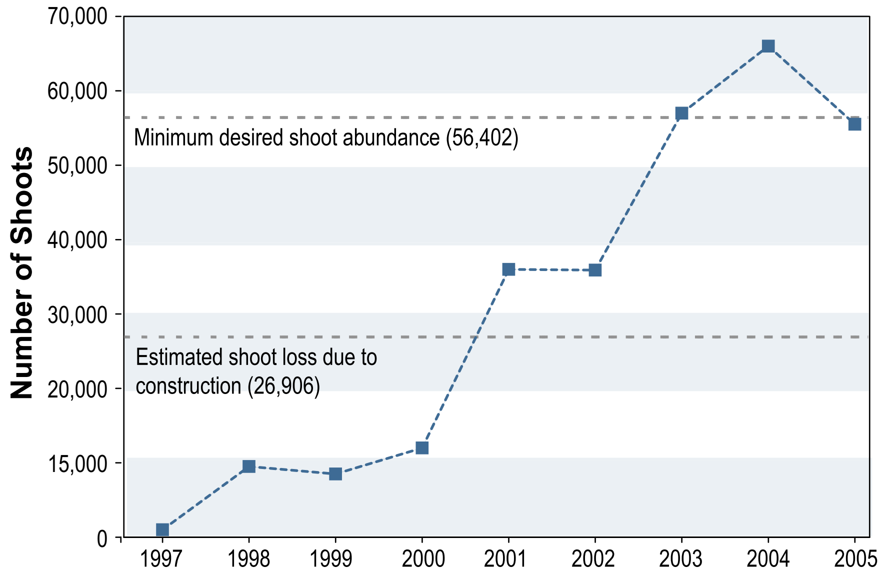
The impact of derelict nets on marine habitat is significant. Rocky reef habitat is particularly susceptible to net entanglement, making the habitat unusable by species that typically inhabit these areas. Derelict nets, sometimes four to six layers deep, inhibit access to critical habitat and trap fine sediments that can suffocate the sedentary life of valuable rocky reef habitat, substantially degrading the habitat's natural function.

Lost and abandoned fishing gear is also a hazard to humans. It can entangle divers and swimmers, with the threat to divers being especially great. Derelict fishing gear also damages propellers and rudders of recreational, commercial, and military vessels, as well as cruise ships, putting crews and passengers in danger. Derelict fishing gear has been known to entangle and overturn small boats and is a navigational hazard for all vessels.

c. Eelgrass Restoration in Puget Sound

The restoration of eelgrass in Puget Sound has received growing attention since the late 1980s. Researchers from Battelle's Marine Research Laboratory in Sequim have been working on eelgrass restoration for several years. It is difficult to predict the precise outcome of eelgrass restoration projects. However, based on field studies at the Clinton ferry terminal, Holmes Harbor, Grays Harbor, and several other locations in the Pacific Northwest, researchers in Sequim have developed an adaptive management framework (Thom et al. 2005) that provides an improved understanding of light, substrata, nutrients, temperature, wave energies, currents, grazing, and other factors that control the development of eelgrass. By understanding these factors, sites for future restoration can be evaluated.

Figure 3-27. Eelgrass density following transplant, 1997-2005. The total number of eelgrass shoots that developed from the transplanting project has resulted in a net gain in eelgrass near the Clinton ferry terminal. To offset the unavoidable loss of approximately 26,000 shoots by construction of the new terminal, restoration efforts reinstated approximately 60,000 replacement shoots. After completion of construction in 2001, eelgrass shoot abundance exceeded pre-construction numbers.
(Source: PNNL)



Status and Trends

Five years of monitoring eelgrass restoration following initial planting at the Clinton ferry terminal revealed several interesting factors about eelgrass restoration. For example, the shoot density one year after planting is a good indicator of the possible density five years after planting (Figure 3-27).

d. Marine Reserves and Conservation Tools

Brackett's Landing Shoreline Sanctuary is a 22-acre underwater park located near the ferry terminal in Edmonds. Established in 1970, it is part of the network of reserves being developed by WDFW to manage rockfish and other rocky habitat species. The reserve is one of the most popular dive sites in Puget Sound and contains human-made trails consisting of concrete blocks, ropes, and other artificial objects to attract fish and other marine organisms. Large anemones cover much of the artificial structures. Many marine mammals, such as harbor seals, sea lions, seabirds, and diving ducks may be found at the site.

Several times each year, WDFW scientists in scuba gear conduct visual surveys to assess fish populations within the reserve. Fish species are identified, counted, and measured along permanent transect corridors within the reserve. These observations provide parameters such as fish density, size distributions, and population sizes that can be compared with similar surveys conducted at nearby areas open to fishing.

The Edmonds site has become an important reference area at which to study the effects of harvest closures on fish populations. Research conducted at the site has indicated that a 30-year absence of harvesting has resulted in dramatically increased fish density, individual sizes, and reproductive outputs, compared with these features at other fished sites. The largest lingcod to be caught in Puget Sound was landed at this site. Healthy beds of eelgrass separate the intertidal and subtidal areas, and bladed kelps and sea lettuce are found on site. Species of fish that are found in the reserve are listed in Table 3-3.

Common Name	Scientific Name
Copper rockfish	Sebastes caurinus
Quillback rockfish	Sebastes maliger
Lingcod	Ophiodon elongatus
Cabezon	Scorpaenichthys marmoratus
Kelp greenling	Hexagrammos decagrammus
Painted greenling	Oxylebius pictus
Black rockfish	Sebastes melanops
Pipefish	Sygnathus leptorhynchus
Juvenile codfish	Gadus macrocephalus
Surf perch	Embiotocidae spp.
Shiner perch	Cymatogaster aggregata

Table 3-3. Fish species in Edmonds underwater park. Includes several rock fish and nearshore species. (Source: WDFW)

11. Recommendations

In the *2002 Puget Sound Update*, recommendations were provided, based on the results from the studies reported. Progress made on the recommendations for physical environment and habitat are briefly summarized in the following table:

Recommendation from the 2002 Update Report for Toxic Contaminants	Progress made through 2006 on recommendations in the 2002 Update Report
Resource managers and planners should investigate opportunities to integrate the developing understanding of climate cycles into ecosystem-based management of the region's habitats and species.	The Climate Impacts Group (under contract to PSAT) summarized research and monitoring findings on impacts of climate change to Puget Sound ecosystems and species. This document can help serve as a launching point for incorporating climate information into management and planning.
Shoreline modification associated with single-family residences is a major component of total shoreline modification. State and local governments should review policies that regulate shoreline modification for singe-family residences, to ensure patterns of modification are balanced with the protection of Puget Sound.	Recent updates to the guidance for Shoreline Master programs by Department of Ecology call for a precautionary approach to shoreline armoring including the use of buffers and setbacks where feasible and a preference for softer alternatives to bulkheads and other armoring. The Puget Sound Action Team released a report in September 2006 on evaluating the effectiveness of several of these alternative shoreline treatment technologies.
Scientists need to better understand the role of groundwater in Puget Sound's freshwater budget.	No progress to report.

Moving forward on Puget Sound Science

In looking ahead to what recommendations to report on in future editions of the *Puget Sound Update,* it makes sense to focus on the goals and strategies that have been recommended in *2006 The Puget Sound Partnership Final Report*, the PSAT *2007-2009 Conservation and Recovery Plan for Puget Sound* and the 2006 PSAMP Review. Collectively, these three sources provide targets and goals developed and supported by a large scientific community and reflect both short-term (two year) and long-term considerations for protecting and restoring Puget Sound's health.

The following bullets summarize the goals and strategies put forth in by the Puget Sound Partnership, PSAT and PSAMP that are related to physical environment and habitat (Chapter 3 of this report). Progress towards these goals and strategies will be reviewed in the next edition of the *Puget Sound Update*.

Puget Sound Partnership Final Report (from Appendix A):

Goal: Puget Sound Habitat is protected and restored.

- The amount, quality, and location of marine, nearshore, freshwater, and upland habitats sustain the diverse species and food webs of Puget Sound lands and waters.
- The amount, quality, and location of marine, nearshore, freshwater, and upland habitats are formed and maintained by natural processes and human stewardship so that ecosystem functions are sustained.

2007-2009 Conservation and Recovery Plan for Puget Sound

Priority 5: Protect functioning marine and freshwater habitats.

Strategies:

- Preserve functioning habitats through a variety of conservation tools.
- Help effectively update and implement regulations that protect functioning marine and freshwater habitats.
- Integrate and implement local watershed, salmon recovery, and other plans through regulatory and voluntary approaches.
- Prevent the introduction of new aquatic nuisance species in Puget Sound through regulatory and volunteer approaches.
- Develop a network of sustainable resources to support Soundwide landowner education and stewardship.
- Identify and fill information needs to monitor and improve the effectiveness of protection strategies.

Priority 6: Restore degraded marine and freshwater habitats.

Strategies:

- Restore degraded habitats by restoring habitat-forming processes.
- Plan and undertake large-scale nearshore restoration initiatives through Puget Sound Nearshore Partnership.
- Improve restoration projects by applying the best scientific principles and a process-based approach.
- Improve and streamline permitting for restoration projects.
- Control and stop aquatic nuisance species from spreading and rapidly and effectively respond when **any new species are detected.**

The Role of Science

Strategies:

- Continue ongoing monitoring of the status and trends of key components of the Puget Sound ecosystem.
- Provide scientific information to stakeholders, decision-makers and the public.

- Direct new monitoring to focus on the effectiveness of management activities and policy initiatives.
- Develop a roadmap to prioritize, finance and conduct focused research on emerging topics or research questions that are brought forth through PSAMP and science programs.

Detailed recommendations for further research and monitoring

The following recommendations are an outcome of the 2005-2006 PSAMP review and have been included as recommended actions in the *2007-2009 Puget Sound Conservation and Recovery Plan*. Progress towards these and previous recommendations will be reported in the next edition of the *Puget Sound Update*.

Habitat Characterization

- Map nearshore and subtidal marine habitats so that the amount, distribution, and linkages of habitats can be completely identified. Create a coordinated habitat research team that systematically researches and evaluates scientific habitat studies.
- Inventory and map all Puget Sound marine and nearshore habitats with multibeam sonar and LIDAR.
- Integrate WDFW Hydraulic Project Approval actions with nearshore inventories to monitor changes to the nearshore and to watersheds.
- Improve the science of habitat restoration by developing a systematic framework to map restored habitat and monitor how well restoration mimics natural habitat function.
- Determine the effects of derelict fishing gear on habitats, species, and productivity and monitor amount of derelict fishing gear recovered.
- Track sea-level changes.
- Inventory and measure input of nutrients and other contaminants.

Management of resources

- Use a science-based approach to set goals for habitat abundance and distribution needed to support target species assemblages and productivity.
- Track the amount of areas open to various types of fishing activities.
- Monitor effectiveness of individual restoration projects with restoration efforts that plan for and fund validation and effectiveness monitoring.
- Monitor sediment quality at appropriate spatial scales for informing management actions and tracking the success of cleanup efforts.
- Monitor and assess water quality changes at restoration sites in addition to structural habitat parameters.
- Monitor the amount of nearshore and deepwater habitat disrupted by human activities including filling, dredging, dumping, armoring, and the effects on habitat processes.
- Better integrate mapping and scientific studies with agency management processes.

Processes and function

- Improve the understanding of nearshore ecosystem processes and linkages to watershed and marine ecosystem functions, human health, and species at risk.
- Improve the understanding of and ability to predict the incremental and cumulative effects of restoration and preservations actions on nearshore ecosystems.
- Improve the understanding of the relationships of nearshore processes to important ecosystem functions, such as support of human health and at-risk species.
- Further develop circulation modeling capabilities.